Analysis of Phosphorus in Spring Creek and Sheridan Lake in the Black Hills of South Dakota

by

Ethan Swanson

A thesis submitted to the Graduate Office

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

SOUTH DAKOTA SCHOOL OF MINES AND TECHNOLOGY

RAPID CITY, SOUTH DAKOTA

2004

Prepared by:

____

Ethan Swanson

Approved by:

____

Major Professor

____

Chairman, Department of Civil and Environmental Engineering

____

Dean, Graduate Education and Sponsored Programs

ABSTRACT

This report is part of a watershed study for the Spring Creek basin with the primary focus on Sheridan Lake. It describes the findings of a one-and-a-half year study to determine the current trophic state index of Sheridan Lake and ways to reduce it if necessary.

Gages throughout the basin were used to monitor flow. This information was combined with monthly water quality samples and storm water quality samples to determine mass loading of nutrients along the length of Spring Creek. In-lake sampling at two sites identified phosphorus as the limiting nutrient. It also showed that the lake becomes depleted of oxygen below 25 feet by mid July. The drop in oxygen was accompanied by a rise in nutrient levels in the hypolimnion under anoxic conditions. Statistical analysis of water quality data indicates that Hill City and Palmer Gulch are major sources of phosphorus to Spring Creek and eventually to Sheridan Lake. Both showed large increases in phosphorus and other nutrient concentrations during storm events.

Modeling of the lake determined that a 43% reduction of incoming phosphorus concentration would be necessary to reach the target Trophic State Index (TSI) of 45. In order to reach this level, estimates were made of potential reduction of phosphorus loading in the basin based on implementation of best management practices such as storm water management and stream bank stabilization.

ACKNOWLEDGEMENTS

I would like to thank Patrick Schwickerath for working with me on this project and all the learning that accompanied it; Dr. Scott Kenner for lining up the project and providing guidance throughout; Dan Nebelsick for helping with field work on numerous occasions; Bob Smith, Aaron Larson, and Kevin Goyer of the DENR for their time and advice; and the students and faculty of SDSM&T who went out of their way to offer good advice or different perspectives.

Innumerable people shape your life everyday in ways that cannot be measured as easily as an engineer would prefer. But looking back one can pick out those who made a big difference with continual influence and encouragement. On that note I would like to thank my parents for their love and encouragement.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

In 2002 Sheridan Lake was put on the 303(d) list for high Trophic State Index (TSI). Its TSI value was listed as 51 with a desired level of 45 based on regional characteristics (DENR, 2002). TSI is a measure of lake productivity. The food chain, water temperature, incoming light, and nutrients can all affect the productivity of lakes. But the incoming nutrient load is the driving force that feeds the algae and bacteria that make up the food chain and ultimately determine productivity. To determine the current trophic conditions and to evaluate the effects of nutrient loading, a water monitoring program was initiated for Sheridan Lake and Mitchell Lake in May 2002. The results of the water quality monitoring program were used to estimate nutrient loads to Sheridan Lake and Spring Creek. To estimate the effects of future reductions in nutrient loading, a lake model was developed that modeled the movement of phosphorus within and through a lake. To determine how to get the necessary nutrient load reductions, an assessment of possible watershed remediation measures was conducted with estimates made for potential reduction in nutrient loading based on literature.

OBJECTIVES

The first objective of this study is to determine current nutrient and biologic conditions of Sheridan Lake and calculate the TSI value. The second objective is to estimate the nutrient loadings from individual tributaries in the Sheridan Lake watershed through hydrologic and water quality monitoring. The final objective is to develop watershed restoration recommendations and a nutrient TMDL for Sheridan Lake.

WATERSHED CHARACTERISTICS

Sheridan Lake lies on Spring Creek about 20 miles southwest of Rapid City and 5 miles northeast of Hill City (Figure 1). The lake covers 383 acres with a mean depth of 29.5 feet and a maximum depth of 90 feet (GFP 1987). Flow passes out over a 40 foot concrete spillway. The option also exists to withdraw water from deeper levels of the lake through an outlet pipe. It has not been used in recent years due to concerns about its condition. Spring Creek is the primary source of water for the lake. Minor tributaries include Horse Creek and Calumet Creek. Spring Creek above Sheridan Lake drains approximately 127 square miles. Metamorphic slates and schists along with granite rock primarily underlie this part of the basin. These form the Central Crystalline Area of the Black Hills (USDA, 1990) that covers the majority of the study area. The upper edge of the basin where Spring Creek starts is in the Madison Limestone. The watershed’s major soil types are Pactola, Buska, Mocmont, and Stovho (USDA, 1990). The Pactola series of soils, which cover most of the basin, were formed by the weathering of materials in steeply tilted metamorphic rock. The Buska series descends from micaceous schist while the Mocmont formed from material weathered from granite. These two series generally occur in the upper reaches of the basin in the Harney Peak area. The Stovho series formed from the weathering of limestone and calcareous sandstone and is found in the upper reaches of the basin in the area underlain by the Madison Limestone (USDA, 1990). Digital Elevation Models of the area show the average slope to be approximately 20%. Much of the land is located within the Black Hills National Forest and is

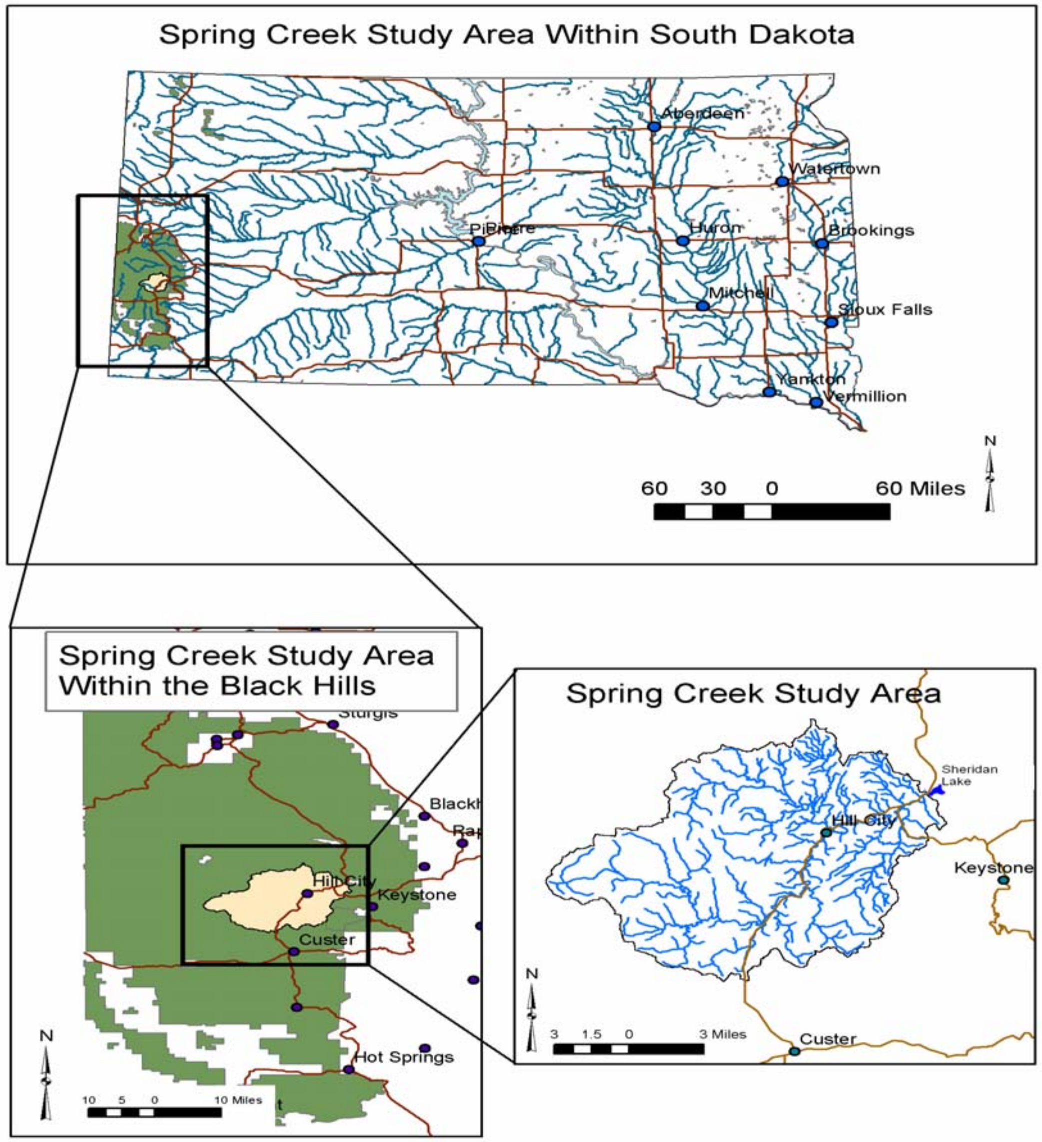


Figure 1. Sheridan Lake and Spring Creek Study Area

predominantly covered by ponderosa pine. Other cover includes grasslands and hardwoods (Klassen, 1997). According to National Weather Service records, the average precipitation at Hill City is 20.4 inches with over 70% of it coming in the months of April through August and over 50% falling in the months of May through July.

LITERATURE REVIEW

Modeling

Modeling of any kind is begun with specification of the problem. A model should meet the customer's requirements. The modeler also needs to know any physical, legal, or economic restraints that are present. Knowledge of what is possible for modeling is often helped by gathering existing data (Chapra 1997).

Water quality models can be broken into two categories. The first type of model is an empirical one. Empirical models usually work with averaged conditions. The simplicity of such models generally result in low data requirements. However, the same simplicity can limit model applicability. The second type of model is theoretical. These types of models work with direct simulation of physical, chemical and biological processes. Data requirements are higher as are computing capabilities and user expertise. Theoretical models are especially useful in cause-effect relationships. Although applicable to a broader range of problems, they are not necessarily more accurate than simpler empirical models (Walker 1996).

Sometimes, existing models are insufficient to deal with the specified problem and the development of a new model is required. In such cases, the model will require theoretical development and numerical specification and validation (Chapra 1997).

The first part of the theoretical development is to specify the required variables, parameters, and associated equations. Here it is useful to know what data has been gathered as well as what types of data can be gathered. The second part comes in choosing the model's complexity. The model needs to be consistent with the data that is and will be available and be consistent with the specified problem requirements. Numerical specification and validation involves checking a model's mass balances, testing it against simplified solutions, using it under a wide range of conditions, plotting graphical results, and having various users test it to determine if there are any faults.

Once a model is up and running, it should be calibrated against field results. The first step is to calculate the model's physical parameters. These are the functions that drive the model and can be determined from available data. Other model parameters are adjusted until a best fit is attained between modeled results and field data. The final step is to establish the model's robustness. This is usually done by comparing the model results to a second set of field data. The more observations that can be confirmed by the model, the better and more robust the model is (Chapra 1997).

Previous Studies

A report by the South Dakota GF&P (1964) provides water quality data from Spring Creek taken in 1962-63 and a sample from Sheridan Lake taken in November 1962. Spring Creek data shows Hill City sewage discharge as the main source of nutrients. Sheridan Lake's total phosphate concentration is reported as 0.10 mg/L while the NH4 concentration is reported at 2.76 mg/L.

The Department of Health (1969) cited silt and bacteria as the major pollutants in Spring Creek. The major source of pollutants was listed as wastewater, with cattle grazing, road construction, and timber activity contributing lesser amounts. The report went on to state that nitrogen and phosphorus were contributing to aquatic plant and algae growth in Mitchell and Sheridan Lakes. Detergents were listed as a source of phosphorus and also noted for causing buildups of foam within Spring Creek.

Composite samples from Sheridan Lake were collected by the Black Hills Conservancy SubDistrict in summer 1971. They showed total phosphate concentrations in Sheridan Lake of 0.6 to 0.9 mg/L. The chemical formula for phosphate is four oxygen atoms and one phosphorus atom. The atomic weight for oxygen is 16 while the weight of phosphorus is 31. Subtracting the weight of oxygen in phosphate can give a total phosphorus concentration. This corresponds to total phosphorus concentrations of 0.2 to 0.3 mg/L.

A US Environmental Protection Agency (1976) report based on samples taken in April, July, and September of 1974 stated that the lake was nitrogen limited and eutrophic. The report also estimated pre-1973 phosphorus contributions from Hill City at 465 kg/yr and estimated the precipitation load of phosphorus at 25 kg/yr. Phosphorus loading dropped after Hill City constructed waste water lagoons in 1973. Based on data collected in 1974 and 1975, the overall nutrient loading to the lake was estimated at 295 kg/yr of phosphorus and 5,250 kg/yr of nitrogen with Spring Creek accounting for 74.6% and 51.7% respectively of those totals. Analysis of the EPA data showed oxygen depletion below 20 feet in the summer and high chlorophyll-a values (26.5 & 34.5 ug/L) during the July sampling when “samplers observed an algal bloom in progress.” The nitrogen limitation in the EPA report was based on ratios of inorganic nutrients. However, a further analysis of the EPA data numbers from the study showed phosphorus limitation in five of the six samples in terms of total nutrient concentrations. Phosphorus limitation is indicated by a nitrogen to phosphorus ratio of greater than 7.2. A ratio of 7.2:1 is roughly the ratio of nitrogen to phosphorus in plant matter. So a ratio greater than that indicates phosphorus as the limiting nutrient (Chapra, 1997). All three sampling dates had good correlation between TSI values based on chlorophyll a and total phosphorus. The report stated that orthophosphorus values were unreliable due to holding time. A summary of the EPA data with analysis is shown in Table 1.

Table 1. EPA Nutrient Data from Sheridan Lake

	Date	N:P inorganic	N:P total	TP mg/L	TSI TP	CHL a ug/L	TSI CHL a	Secchi in	TSI Secchi
Site 1	4/25/1974	14.0	23.7	0.027	51.7	8.1	51.1	108	45.4
near dam	7/15/1974	2.3	9.3	0.059	63.0	26.5	62.7	108	45.4
	9/12/1974	5.6	26.3	0.027	51.7	4.4	45.1	96	47.1
Site 2	4/25/1974	7.5	22.9	0.028	52.2	8.3	51.3	102	46.3
near SC inlet	7/15/1974	2.5	6.7	0.072	65.8	34.5	65.3	126	43.2
	9/12/1974	5.0	29.3	0.014	42.2	10.8	53.9	96	47.1

DENR data from 1979 showed oxygen depletion below 5.5 meters and a mean TSI value of 52.6 with a range of 47.4 to 57.4 Data collected by Bauman (1980) from 1979-1980 showed oxygen depletion below 5 meters and TSI values ranging from 41 to 57 with a mean of 50.3. TSI values were calculated using Secchi Disk, total phosphorus, and chlorophyll-a. In a report for the SD DENR, Harms (1981) cites streamside grazing, domestic wastes, roads and highways, and natural erosion as major sources of pollution in the Spring Creek Basin with poor tillage methods and silvicultural practices as lesser sources.

A report by Bell, Galyardt & Associates (1981) analyzed water quality data collected in the Spring Creek Basin during the 1970's. It reported high phosphate values coming from Newton Fork Creek, the land just above Sheridan Lake, the springs that feed the creek, and Bobcat Gulch. The lowest values were reported at Sunday Gulch, Palmer Creek, and below Sheridan Lake. Analysis of data show the mean phosphorus concentration above Sunday Gulch to be 0.150 mg/L while below Sunday Gulch it is 0.069 mg/L. The median values at both places however were approximately 0.03 mg/L.

The 1988 “Black Hills Lakes Preliminary Study” was prepared for the US Forest Service by the SD DENR (1988). It lists potential sources of sediment as logging and forest service roads, especially those along creeks. Also listed are old mining sites, streamside grazing, and natural erosion of hillsides. Depths of sediment are calculated in four different bays and inlets: Spring Creek Inlet, Horse Creek Inlet, Calumet Creek Inlet, and North Lake Inlet. The loss of volume in these inlets due to sedimentation ranged from 20 to 40%.

In July and August of 1989 the DENR collected surface and bottom water samples from Sheridan Lake and made recordings of Secchi Disk depth. TSI for the Secchi Disk readings were 45 and 50.1 while the phosphorus TSI values were calculated as 58 and 64. Of note was the increase in bottom water phosphorus concentration from 0.098 mg/L in July to 0.610 mg/L approximately one month later.

The United States Geographical Survey (USGS) installed a flow gage on Spring Creek above Sheridan Lake and started recording flows on October 1, 1990. Flow measurements to establish depth discharge relationships were accompanied by water quality samples.

Mudumala (1991) collected water quality samples and profile information from 3 different sites on Sheridan Lake. Data was collected between April and September 1991.

By August, oxygen levels were close to zero below 15 feet. The TSI values averaged over the entire time period were 46.8 at the deep site near the dam, 49.8 near the middle of the lake, and 50.4 in the shallower waters of Spring Creek Inlet.

Throughout the 1990's DENR collected water quality information on Sheridan Lake. TSI data from 1991-1995 averaged 48.0 for the Secchi Disk and 50.6 for total phosphorus. Values were highest in 1991, 1993, and June 1995. Lower values were recorded in 1992, 1994, and the second half of 1995. An August 2001 profile shows oxygen concentrations of less than 1 mg/L below 7 meters. Chlorophyll a samples taken from 1991 to 2001 had an average TSI calculation of 49.7 with the highest values of each year occurring in August.

WATER QUALITY MONITORING PROGRAM

The objectives of the water quality monitoring program were to estimate the sediment, biological and nutrient loadings from the individual tributaries in Sheridan Lake and Mitchell Lake watershed through hydrologic and chemical monitoring.

Measuring Flow

Initially 22 monitoring stations were established in the watershed (Figure 2). All stations contained equipment to monitor the water level. The equipment included two R2 units, six OTT Nimbus bubble sensor units, and 14 OTT thalimedes units. Thalimedes and R2 units use a floating device connected to a pulley to keep track of water levels. Nimbus units use a bubbler and water pressure to measure depth. Periodic flow measurements using in-stream current meter methods were made to establish stage-discharge relationships so that a continuous flow record could be developed for each station. A total of 125 flow measurements were made at 19 stations. Flow at the outlets of Sheridan and Mitchell Lake was based on downstream flow measurements. Flow at SCT-1 was determined from the USGS gage above Sheridan Lake. Most flow measurements were made using either a pygmy meter or a Price AA flow meter. For small shallow flows, either a 3 inch Parshall flume or velocity estimates of floating of objects was used to determine discharge. Stations were set in the Spring of 2002 and removed for the Winter in November 2002. Based on lack of adequate stage discharge information, stations NCT-2 and LSCT-3 were discontinued. The rest of the stations were reestablished during March 2003 and completely removed in August 2003. Stage-discharge relationships were constructed using a method described by Gupta (1989). The relationship is as follows:

(1) $Q = A(h \pm a)^n$

where Q = discharge, h = gage height, a = stage of zero flow, and A and n = constants. Winter flows were based on unofficial USGS estimates (Williams, 2003). Problems keeping the batteries of the Nimbus units charged led to some gaps in the data. These gaps were filled by relating flow at the station to that of nearby stations. At stations where stage discharge relationships were not present, the flow was estimated as a percentage of the USGS gage.

Stage data was periodically downloaded from each station using a laptop computer and the Hydras program. The program summarized 15 minute and daily gage height. The stage-discharge relationship for each gage was applied to the stage data to calculate daily flow values.

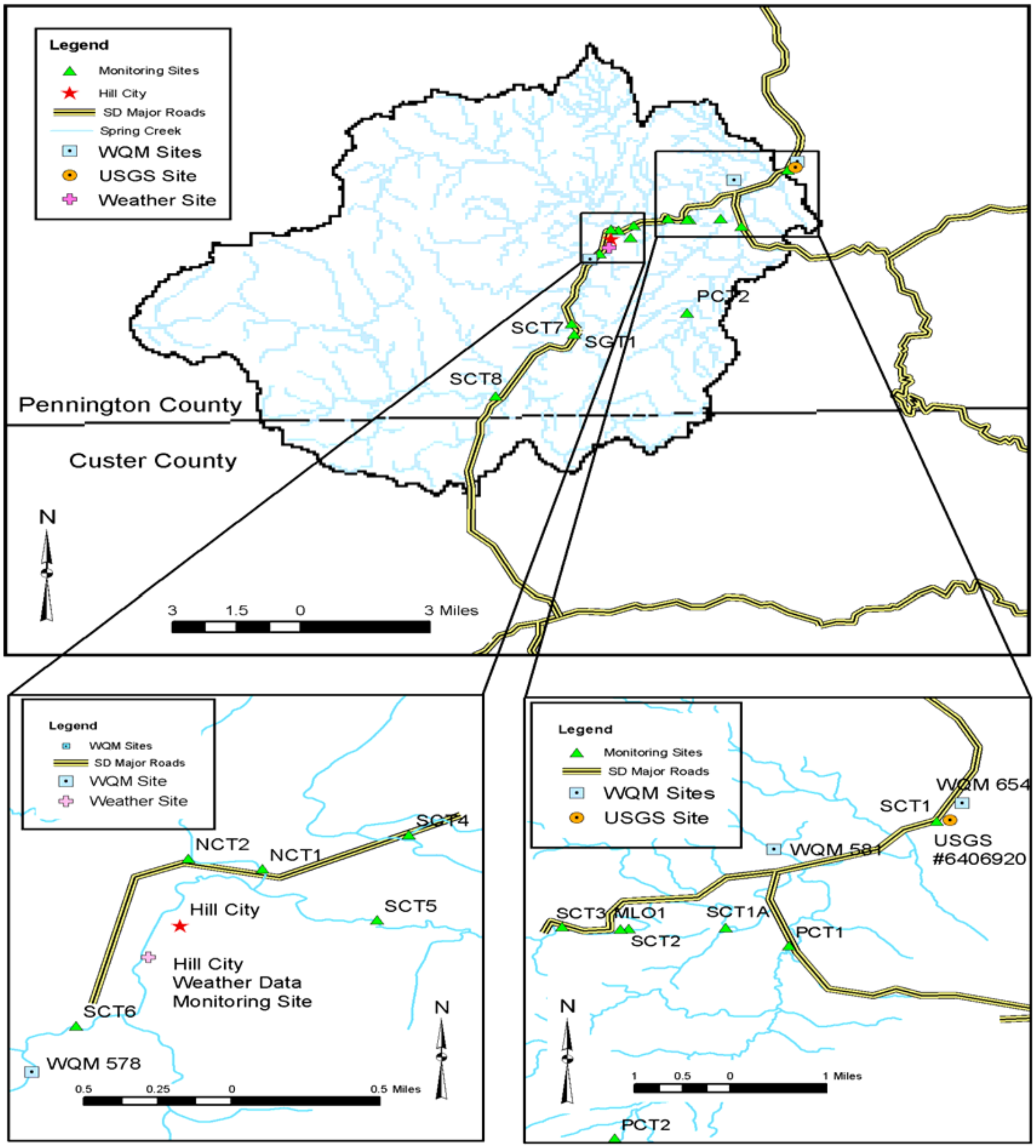


Figure 2. Spring Creek Monitoring Sites

Sampling of Lakes and Streams

In order to assess the quality of lake waters in the basin, Sheridan Lake and Mitchell Lake were periodically sampled. The sampling schedule was for surface and bottom water monthly samples of Sheridan Lake and monthly top samples of Mitchell Lake. The shallow depth of Mitchell Lake, less than 10 feet, meant that it did not thermally stratify. Consequently, it was decided to only sample from the top of the water column. Sheridan Lake was sampled in two different locations, SL-1 and SL-2, while Mitchell Lake was only sampled in one location near the dam. The sampling locations in Sheridan Lake as well as depth contours are shown in Figure 3.

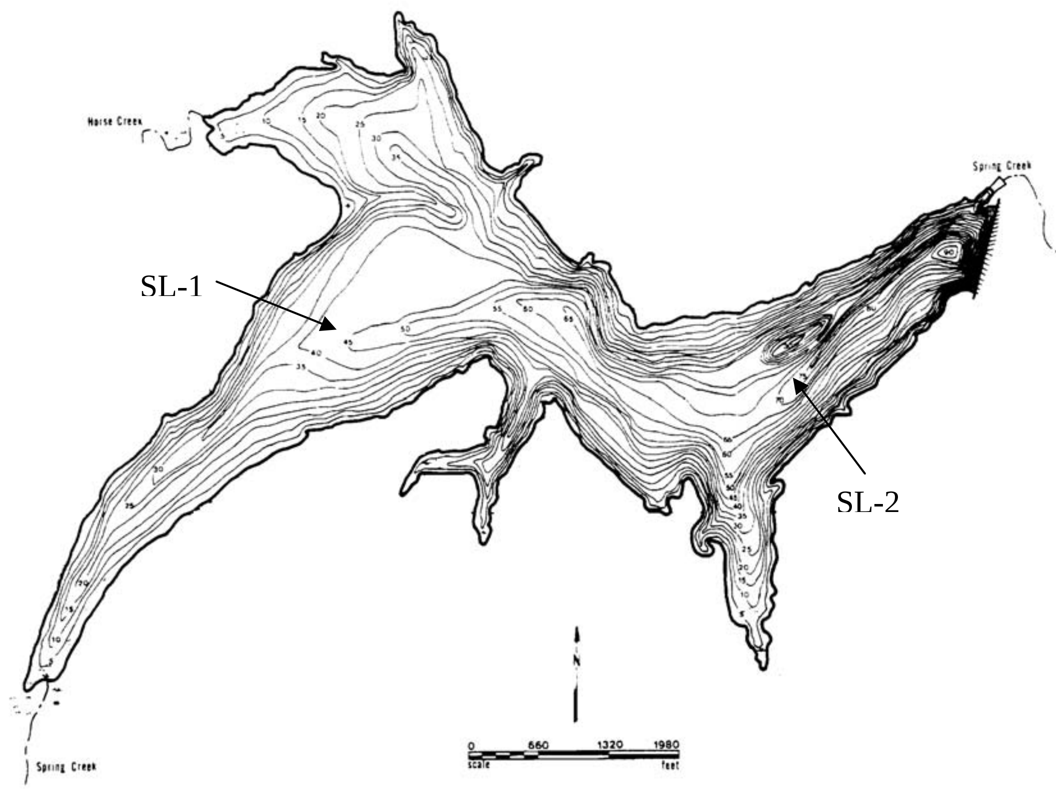


Figure 3. Sheridan Lake sample locations

Due to weather and ice conditions neither lake was sampled in November 2002, or March 2003. In addition, Sheridan Lake was not sampled in December 2002. Grab samples of water were analyzed for nutrients and solids. Top samples were also analyzed for fecal coliform bacteria and chlorophyll-a. Water column zooplankton samples were made using a Wisconsin D-net with 80 μm mesh. Two elutriate samples were taken from Sheridan Lake in March 2003 and one additional sample was taken from Mitchell Lake in June 2003. Sediment for the elutriate samples was taken with a petite ponar sampler. Bottom water samples were taken using a Van Doren sampler. During months with open water, top samples were taken from approximately 3 feet down using the Van Doren sampler. In the winter, samples were taken from the surface with a pitcher due to problems with the Van Doren getting ice covered. A submerged macrophyte survey of Sheridan Lake was conducted in August 2003. On the same day, three sediment samples were taken from the lake to be analyzed for total phosphorus content. Further data from Sheridan and Mitchell Lakes was gathered by using an YSI Sonde to measure lake temperature and dissolved oxygen levels. Measurements were taken at 3 foot intervals from the surface to the bottom. In this way a profile at each location could be made.

Streams were sampled on a monthly basis from May to November 2002 and in May 2003. In addition, a mid winter and two snowmelt samples were collected. Storms that generated runoff were periodically sampled to help determine the aspect of storm loading. Stream samples were analyzed for physical, chemical, and biological constituents. This included nutrients, solids, bacteria, and chlorophyll-a. Further knowledge of stream characteristics was achieved by sampling for benthic macro invertebrates and conducting a physical habitat characterization following EMAP protocol (Peck et al. 2001). All water quality samples were collected following methods demonstrated by DENR personnel or referenced from the SD DENR Standard Operating

Procedure manual. All water samples were analyzed by Energy Labs, a commercial analytical lab in Rapid City. The SD State Department of Health analyzed the elutriate samples.

Quality Assurance\Quality Control

In order to insure the quality of the monitoring results, a quality assurance\quality control (QA\QC) program accompanied the samples. For every ten samples taken, a blank and duplicate sample were also taken. Blank samples evaluate the laboratory procedures and consist of using distilled deionized water in place of a normal sample. Duplicate samples are taken from the same place at the same time and are designed to determine sample variability. Analysis of the lake QA\QC data showed that the average for the duplicates samples had a 5% higher total kjeldahl nitrogen value, 19% higher total phosphorus value, and 1% lower total organic carbon value than the original samples. The complete QA\QC data are contained in Appendix A.

DATA ANALYSIS

Limiting Nutrient

The primary problems of excess nutrients are plant growth and production increases that result. Plants utilize nutrients from the water in proportion to their stoichiometry. The general nitrogen phosphorus ratio (N:P) for aquatic plants is 7.2 to 1 (Chapra, 1997). A ratio larger than this indicates excess nitrogen and limited phosphorus while a lower ratio indicates the reverse. Once the limiting nutrient has been identified from water quality samples, possible measures to change productivity can be considered.

Lake samples were analyzed for nutrient concentrations of carbon, nitrogen, and phosphorus. Carbon was analyzed for total organic and dissolved organic amounts.

Nitrogen was analyzed as total kjeldahl nitrogen (TKN), ammonia, and nitrates and nitrites. Samples were also checked for total phosphorus and orthophosphate. Nitrates/nitrites and ammonia represent the portion of nitrogen immediately available for plant growth. TKN is the sum of ammonia and organic nitrogen. TKN represents the total amount of oxidizable nitrogen. Orthophosphate is phosphorus immediately available for plant consumption while total phosphorus represents organic and inorganic phosphorus as well as particulate and non-particulate phosphorus (Chapra, 1997). The rapid recycling of phosphorus in the epilimnion means that total phosphorus may be the most important measurement when determining the overall lake condition (Wetzel, 2001). All nutrient concentrations were given in mg/L of the primary nutrient. For instance, ammonia was reported as the amount of nitrogen (N) in mg/L in the sample attributed to ammonia. This made for easy calculations of nutrient ratios. Total nitrogen was calculated as the nitrates and nitrites plus TKN. Certain precision problems did occur as a result of the reporting limits. The limit to which different nutrients can be detected varies. Energy Labs had reporting limits of 0.05 mg/L for nitrates and ammonia, 0.5 for TKN, and 0.0040 for total phosphorus. When a substance is below the reporting limit, SD DENR procedure is to record one half the reporting limit. Although statistically sound, a quick look at the numbers shows that the N:P ratio for all substances reporting below the limit would be 137.5 to 1. In addition, the lower reporting limit for phosphorus meant that it was always found while many nitrogen quantities ended up below the reporting limit.

Plant growth and the start of the food chain occur where there is sufficient light to start photosynthesis. For this reason, only surface samples were analyzed when considering the limiting nutrient. To remove any bias due to reporting limits, values below reporting limits were listed as zero. Overall the average N:P ratio was calculated as 22.7 to one. The data are shown in Table 2. In addition elutriate samples from Sheridan Lake showed an average N:P ratio of 13.2 to one. These samples were taken from bottom waters, but were taken while the lake was well mixed and are assumed to be representative of overall water concentrations. These numbers indicate that at present the lake is phosphorus limited and best management practices should focus on limiting the input of phosphorus to the lake.

Table 2. Sheridan Lake Surface Nutrient Ratios

Station	Sample Date	Total P mg/L	Total N mg/L	N:P Ratio
SL-1	5/23/02	0.020	0.08	4.0
SL-2	5/23/02	0.023	0.60	26.1
SL-1	6/7/02	0.020	0.00	0.0
SL-2	6/7/02	0.022	0.00	0.0
SL-1	7/10/02	0.016	0.05	3.1
SL-2	7/10/02	0.015	0.00	0.0
SL-1	8/14/02	0.010	0.60	60.0
SL-2	8/14/02	0.010	0.50	50.0
SL-1	9/24/02	0.019	0.60	31.6
SL-2	9/24/02	0.018	0.60	33.3
SL-1	10/21/02	0.034	0.90	26.5
SL-2	10/21/02	0.043	0.70	16.3
SL-1	1/21/03	0.059	0.00	0.0
SL-2	1/23/03	0.043	0.76	17.7
SL-1	2/18/03	0.026	0.56	21.5
SL-2	2/18/03	0.036	1.10	30.6
SL-1	4/15/03	0.010	0.00	0.0
SL-2	4/15/03	0.013	0.57	43.8
SL-1	5/7/03	0.017	0.53	31.2
SL-2	5/7/03	0.035	0.53	15.1
SL-1	6/4/03	0.014	0.56	40.0
SL-2	6/4/03	0.012	0.59	49.2

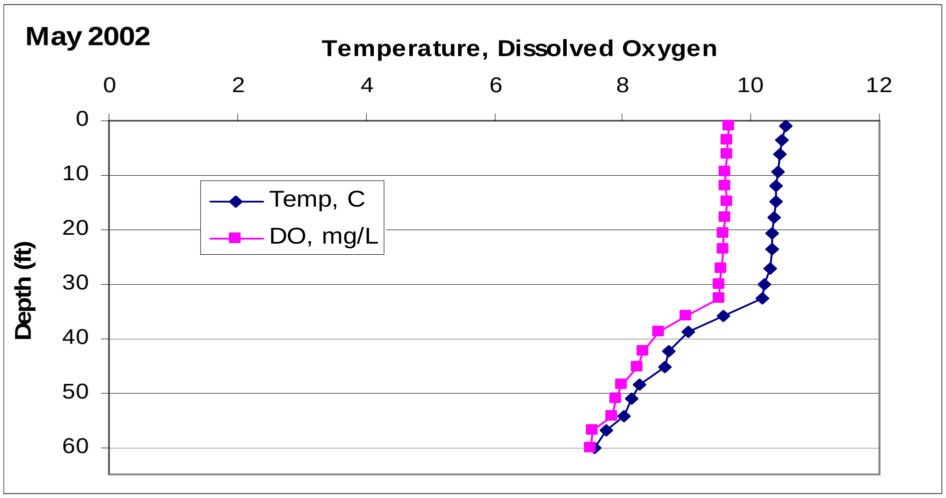
Analysis of the data draws a distinction in that almost all nitrogen values were below reporting limits in the months of June and July 2002. At this time plant growth may have been limited by nitrogen. Another possibility is that nitrogen concentrations may have been present, but below the detection limits. If TKN were present at even half the detection level, a value of 0.25 mg/L, then the N:P ratio would have been greater than 10:1 and phosphorus would be limiting. It is important to remember that at various points of the year plant growth can be limited by nutrients, light, temperature, or even zooplankton grazing (Cooke et al, 1986).

Sheridan Lake Stratification

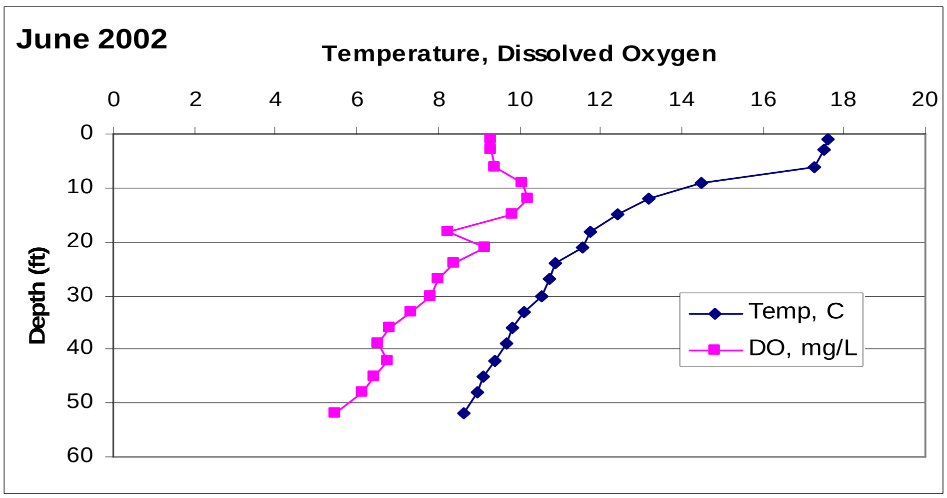
Monthly profiles of dissolved oxygen and water temperature allowed for observation of the stratification of Sheridan Lake. Profiles taken in Sheridan Lake from May 2002 through October 2002 are shown in Figure 4. All profiles shown were recorded at the deeper of the two sampling sites on Sheridan Lake. It can be seen that as the summer progressed, Sheridan Lake became more strongly stratified and the hypolimnion became almost devoid of oxygen.

A pronounced division of the lake into upper and lower layers was evident by the time of the July sampling. This drop in oxygen levels in the hypolimnion was followed by a rise in the total phosphorus concentrations from the bottom samples. By late summer the metalimnion was proceeding downward. By October, Sheridan Lake was mixed to a depth of 50 feet and the total phosphorus concentration had dropped at SL-1. Bottom samples from SL-1 were taken at depths of 35 to 45 feet while samples from SL-2 were taken at depths of 59 to 67 feet. Phosphorus and dissolved oxygen concentrations for the hypolimnion are shown in Table 3.

a)



b)



c)

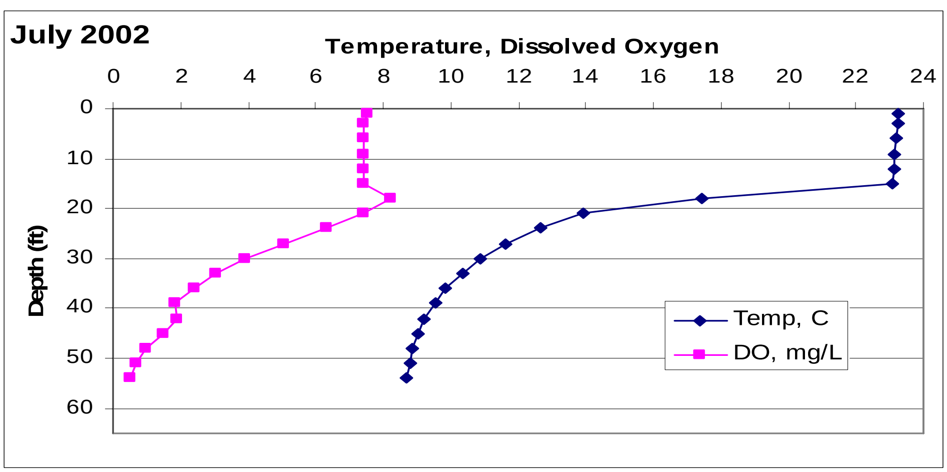
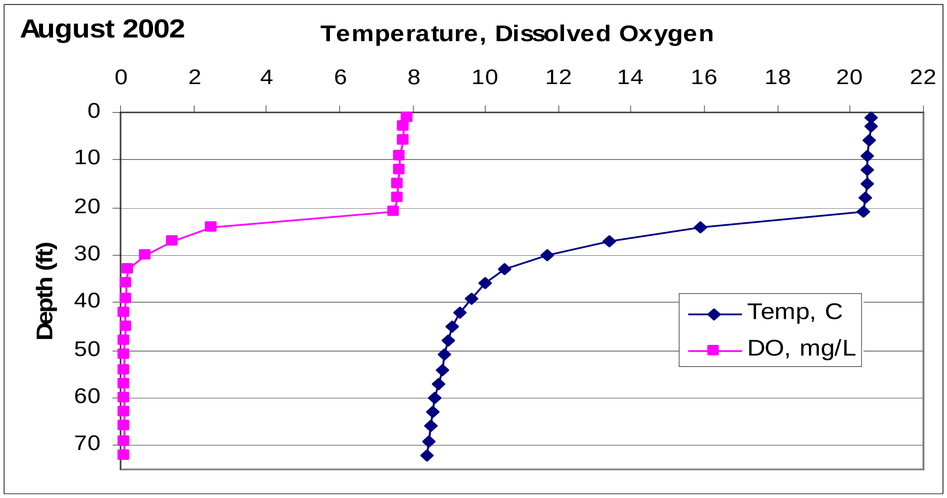
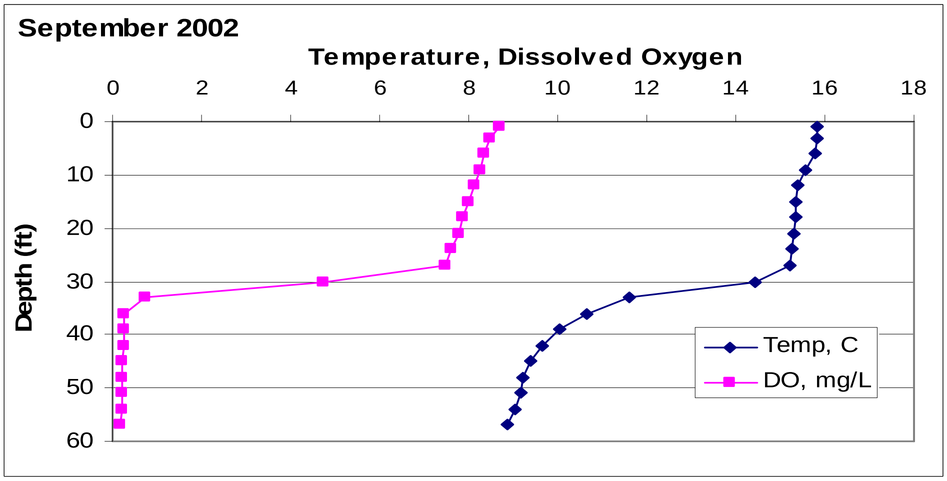


Figure 4. Sheridan Lake Oxygen and Temperature Profiles for a) May b) June c) July d) August e) September f) October 2002

d)



e)



f)

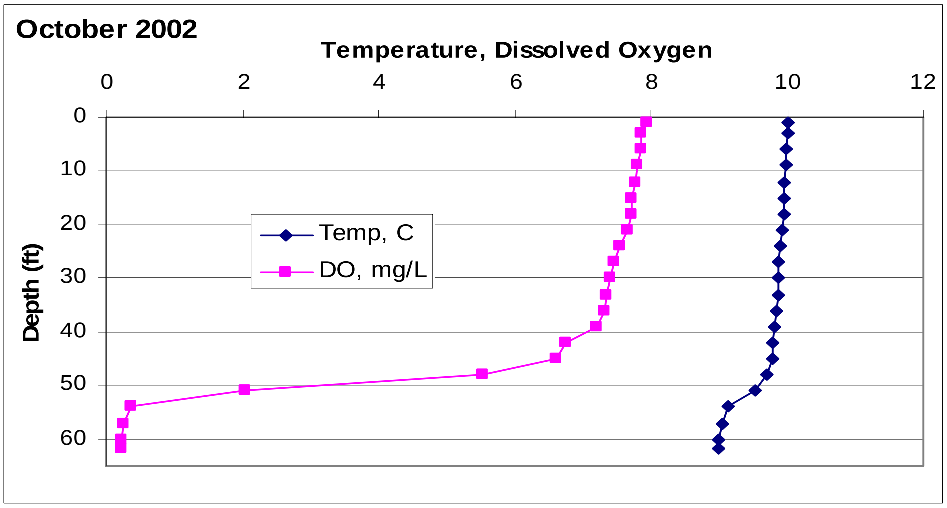


Figure 4. Sheridan Lake Oxygen and Temperature Profiles for a) May b) June c) July d) August e) September f) October 2002 continued

Table 3. Hypolimnion Total Phosphorus and Dissolved Oxygen levels

Date	Hypolimnion DO mg/L	SL-1 Total Phosphorus mg/L	SL-2 Total Phosphorus mg/L
5/23/02	8.29	0.016	0.018
6/7/02	6.48	0.024	0.051
7/10/02	1.45	0.041	0.017
8/14/02	0.20	0.150	0.290
9/24/02	1.22	0.280	0.350
10/21/02	4.70	0.040	0.340

Total phosphorus concentrations are the actual samples taken within a few feet of the bottom of Sheridan Lake while the oxygen concentrations are averaged from throughout the hypolimnion.

Sources of Phosphorus

Though Spring Creek is the main source of phosphorus to Sheridan Lake, additional phosphorus can come from precipitation, groundwater inflow, or the sediments of the lake (Wetzel, 2001). The death and decay of plants, algae, zooplankton and other organic material deplete the lower level of the lake, the hypolimnion, of oxygen. Due to thermal stratification and lack of light for photosynthesis, the lost oxygen cannot be replaced until breakdown of the thermal barrier allows oxygenated water in the epilimnion to mix with the deeper waters. The lack of oxygen in the hypolimnion leads to a loss of oxygen in the sediment-water interface zone. When the oxygen in this zone is consumed, a chemical barrier is removed and phosphorus can diffuse into the overlying waters from the lake bed sediments. The lack of oxygen causes minerals such as iron and manganese that bond strongly with phosphate to become unattached and free the phosphate for movement into the water column (Wetzel, 2001). Chapra(1997) indicates that for the release of phosphorus to proceed, the critical oxygen level within the hypolimnion is 1.5 mg/L. At this point phosphorus is free to diffuse into the overlying water until the reestablishment of oxygen in the sediment-water interface (Wetzel, 2001).

To analyze the sediment-phosphorus relationship within Sheridan Lake, the total phosphorus concentrations were estimated using the monthly samples. The top samples were used to represent the epilimnion, while the average of the top and bottom samples was used to represent the hypolimnion. Hypolimnion phosphorus concentrations can vary widely. Wetzel (2001) presented a graph for the generalized distribution of phosphorus within a eutrophic lake (Figure 5). The average of top and bottom samples was felt to be reflective of actual hypolimnion phosphorus concentrations based on this graph.

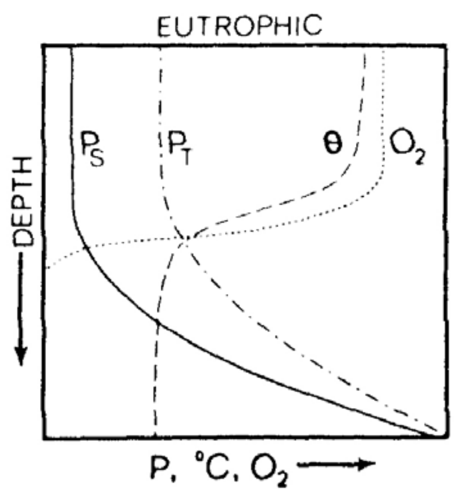


Figure 5. Generalized variation of phosphorus, oxygen, and temperature in a eutrophic lake (Wetzel 2001)

The monthly profile was used to provide the line between the hypolimnion and epilimnion so that the total lake phosphorus concentration average took into account the volume of each part. Stream phosphorus concentrations were applied to each day and multiplied by the flow rate for the incoming and outgoing phosphorus loads. The changes in Sheridan Lake total phosphorus concentration that could not be accounted for by incoming and outgoing flows were assumed to be a result of feedback from the lake bed sediments. For instance, from July 10 to August 14, 2002 the total mass of phosphorus in the waters of Sheridan Lake climbed over 400 kg to a total of over 800 kg, but the difference between the inflow and outflow of phosphorus could only account for 37 kg. The fluctuations in Sheridan Lake Phosphorus content along with the estimated contributions from the sediments and inflowing waters are shown in Figure 6. Because of this phosphorus contribution, sediment samples for phosphorus analysis were taken from Sheridan Lake in August 2003.

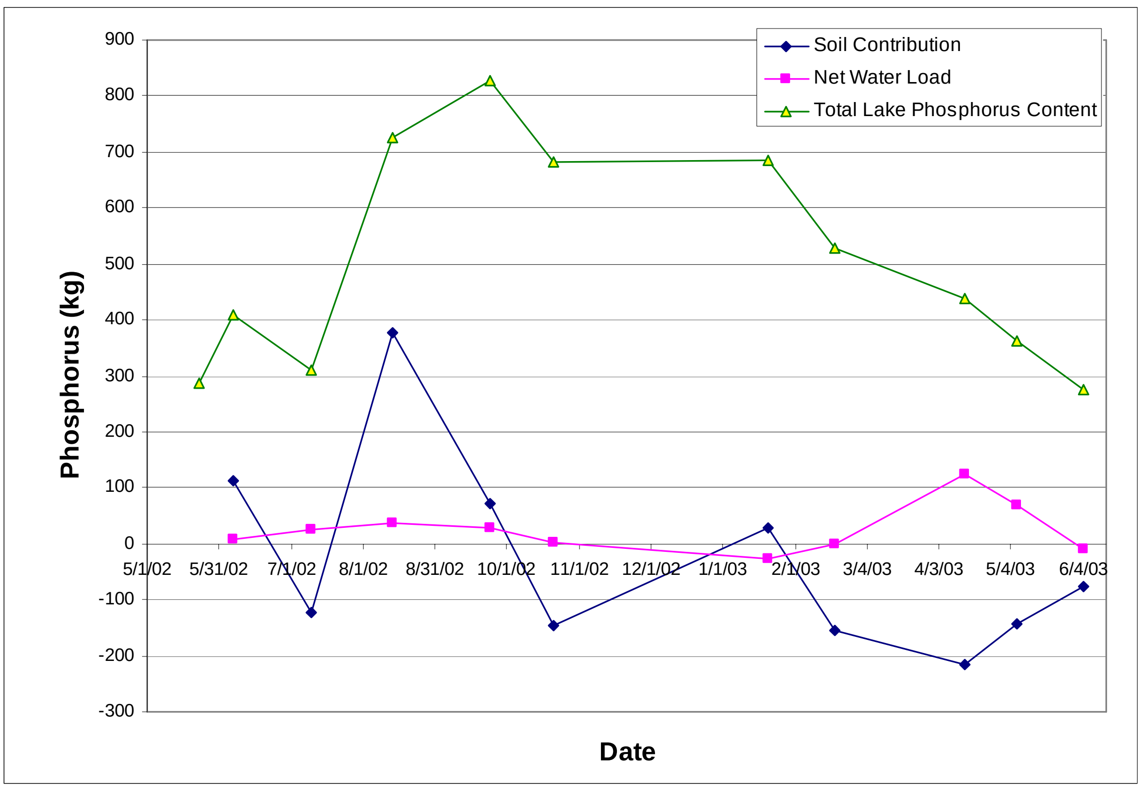


Figure 6. Estimated sediment phosphorus loading in Sheridan Lake

Stream flow rates and phosphorus concentrations enabled calculations that showed Spring Creek is the major source of phosphorus to Sheridan Lake. Much smaller amounts were found to come from Horse Creek and Calumet Creek. The estimates of phosphorus loads were determined by using the FLUX (Walker, 1996) program. FLUX is an Army Corp of Engineers program that uses continuous flow records and concentration values to calculate the mass discharge of any stream constituent. The flow records from each monitoring station along Spring Creek were combined with nutrient data to make estimations of the loading at different points in Spring Creek. The basic assumption of FLUX is that there is a relationship between discharge values and concentration values. For instance, in Spring Creek the highest nutrient values were found when the flow was high due to a runoff producing storm event. Downstream of a point source, it would be expected that discharge and concentration would have an inverse relationship as higher flows would dilute the concentration. FLUX also allows the user to edit or group data to match seasonal patterns or discharge values. Analysis of snowmelt samples collected in March 2003 showed very high concentrations of nutrients. However, the flow records for Spring Creek show relatively low discharge values during the month of March, even during snowmelt. The discharge concentration relationship was therefore different in the winter months than during the rest of the year. With two snowmelt samples, and another sample from January, there was enough data at each station to have a separate winter relationship. With the data and groupings applied to FLUX, phosphorus loadings were calculated. Not all of the stations had sufficient sample data, particularly storm runoff data, to provide adequate calculations. The stations with insufficient data were SCT-5, SCT-3, and PCT-2. The results are shown in Figure 7. All nutrient data used in FLUX is contained in Appendix B.

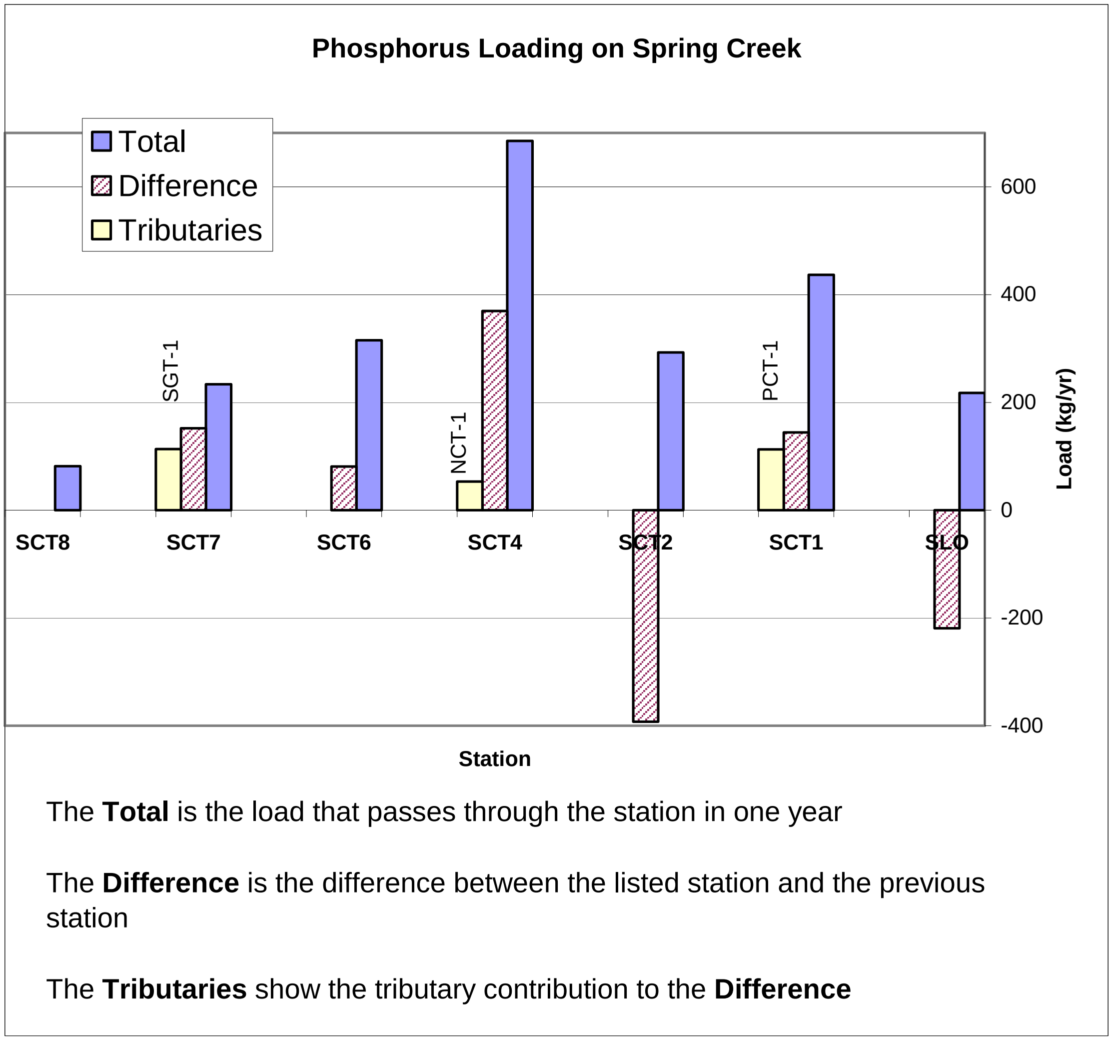


Figure 7. Phosphorus loading along Spring Creek including tributary contributions

As shown in Figure 7, the most significant loading occurs between SCT-6 and SCT-4. Only a small percentage of this is due to the inflow of Newton Fork Creek, the rest is primarily due to storm water runoff from Hill City. Sunday Gulch and Palmer Creek are also significant sources of phosphorus, while Mitchell Lake serves to remove phosphorus from the creek as indicated by the negative difference from SCT-4 to SCT-2.

To quantify the effects of storm water loading, water quality samples were separated into base flow samples and storm flow samples. Storm flow samples were those where surface runoff was generated and thus included snowmelt samples. The base flow samples were run in FLUX by themselves. The results showed the expected loading without storm water loading, and were subtracted from the total load to determine the storm water loading (Figure 8).

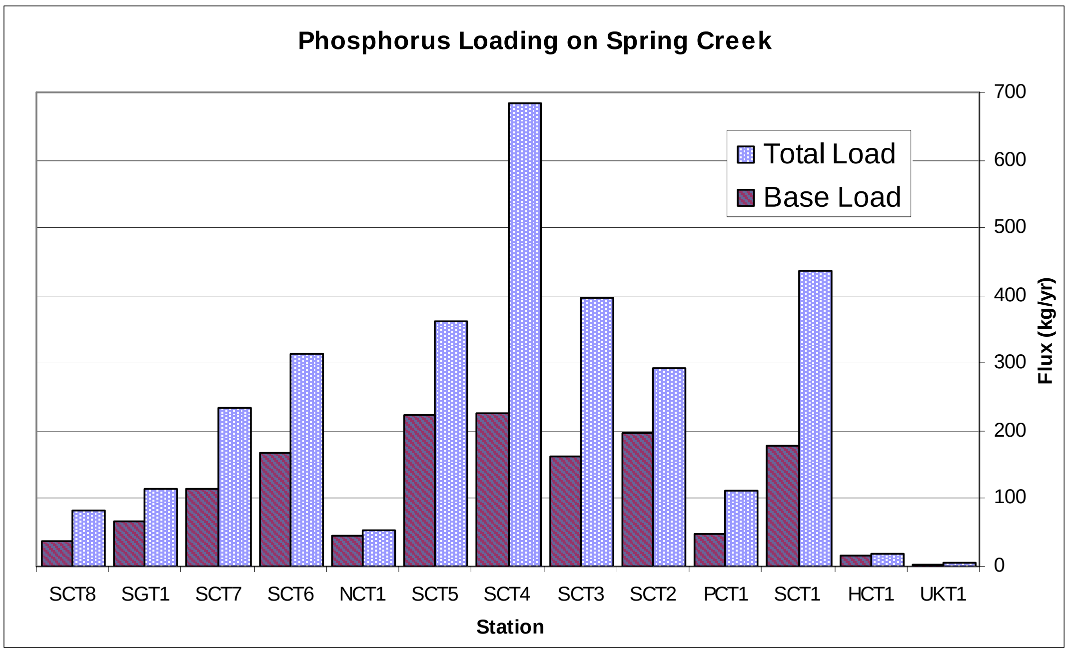


Figure 8. Total Phosphorus Loading vs Base Phosphorus Loading on Spring Creek

The large amount of storm loading is evident at locations such as SCT-4 and SCT-1. The complete summary and division of phosphorus loading is shown in Table 4.

Throughout the Spring Creek Basin, storm water runoff is the dominant source of phosphorus. Notable exceptions occurred at stations SCT-2 and NCT-1. Both of these stations are below lakes which catch and reduce much of the storm water loading.

Table 4. Total Loads, Base Loads, and Storm Loads of Phosphorus along Spring Creek

Station	Total Load (kg/yr)	Base Load (kg/yr)	Storm Load (kg/yr)	% from Storm
UKT1	4.0	2.3	1.7	43%
HCT1	18.7	14.8	3.9	21%
SCT1	437	177	260	59%
PCT1	113	48	65	58%
SCT2	293	196	97	33%
SCT3	396	161	234	59%
SCT4	685	227	458	67%
SCT5	362	224	138	38%
NCT1	53	46	7.0	13%
SCT6	315	167	148	47%
SCT7	234	115	119	51%
SGT1	114	67	47	41%
SCT8	82	37	45	55%

Lake TSI

Collection of phosphorus concentrations, secchi depths, and chlorophyll-a concentrations allowed for the calculation of Sheridan Lake's TSI. The equations for developing TSI were developed by Carlson (1977) and are as follows:

$$(2)\ TSI(SD) = 10(6 - \frac{\ln SD}{\ln 2})$$

$$(3)\ TSI(Chl) = 10(6 - \frac{2.04 - 0.68\ln Chl}{\ln 2})$$

$$(4)\ TSI(TP) = 10(6 - \frac{\ln \frac{48}{TP}}{\ln 2})$$

Secchi depth is in meters, chlorophyll-a and surface phosphorus are in (mg/m^3). The calculated TSI values and a graph charting them over time are shown in Tables 5-7 and Figure 9.

Table 5. Sheridan Lake Secchi Depth TSI		
Date	**Secchi Depth (m)**	**TSI**
5/23/02	3.25	43.0
6/7/02	3.00	44.2
7/10/02	5.00	36.8
8/14/02	2.60	46.2
9/24/02	2.88	44.8
10/21/02	3.63	41.4
1/21/03	3.00	44.2
2/18/03	7.13	31.7
4/15/03	4.25	39.1
5/7/03	4.00	40.0
5/15/03	5.80	34.6
6/4/03	4.75	37.5
	Average	40.3

Table 6. Sheridan Lake Chlorophyll-a TSI		
Date	**Avg Chl-a (mg/m^3)**	**Chl TSI**
5/23/02	7.18	49.9
6/7/02	2.70	40.3
7/10/02	1.53	34.7
8/14/02	3.52	42.9
9/24/02	8.51	51.6
10/21/02	7.99	51.0
1/21/03	6.06	48.2
4/15/03	2.90	41.0
5/7/03	0.50	23.8
5/22/03	0.49	23.6
6/4/03	1.80	36.3
	Average	40.3

Table 7. Sheridan Lake Total Surface Phosphorus TSI		
Date	**Surface Total Phos (mg/m^3)**	**TSI**
5/23/02	0.022	48.4
6/7/02	0.021	48.1
7/10/02	0.016	43.7
8/14/02	0.010	37.4
9/24/02	0.019	46.2
10/21/02	0.039	56.8
1/21/03	0.051	60.9
2/18/03	0.031	53.7
4/15/03	0.012	39.4
5/7/03	0.026	51.2
6/4/03	0.013	41.2
	Average	47.9

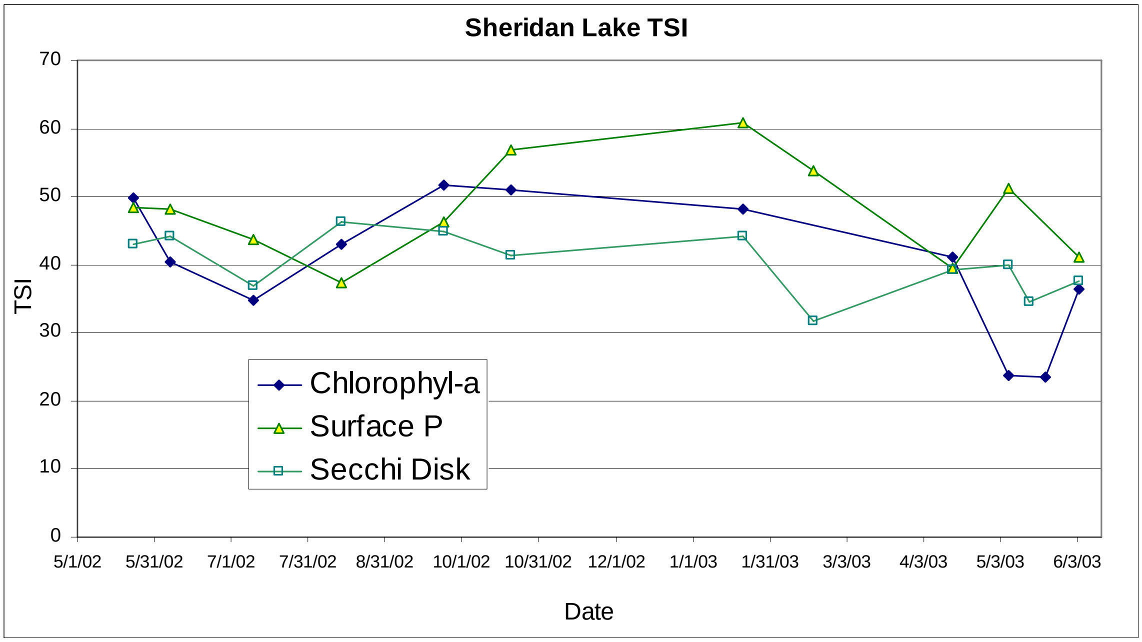


Figure 9. Sheridan Lake TSI Calculations

The results of the TSI calculations varied between the different parameters. DENR (2002) policy is to average the individual values to reach a composite TSI values. However, Carlson (1977) stated in his original proposal that priority should be given to biological parameters in the summer and to phosphorus values the rest of the year. The highest TSI calculations consistently came from the phosphorus values and if phosphorus were to be used as the basis for determining Sheridan Lake's TSI, there would be an inherent factor of safety.

MODELING

As stated earlier, Sheridan Lake is on the 303(d) list for having a high TSI value of 51. Sheridan Lake is within the Black Hills Ecoregion. The state standard for a fully supporting lake in this ecoregion is a TSI of 45.0 or less (DENR, 2002). The TSI of a lake can be calculated by total phosphorus concentration, chlorophyll-a concentration, or

Secchi depth. It was decided to model phosphorus as a representative of TSI. There was phosphorus data from various parts of the lake that would help with calibration. In addition, phosphorus concentrations over time can be modeled with basic equations. Finally, phosphorus is a nutrient that drives lake reactions. In a phosphorus limited lake, excess phosphorus leads to excess plant growth which leads to decreased water clarity. Any change in phosphorus should be reflected by changes in chlorophyll-a concentrations and Secchi depth.

The objectives of the model were:

- Determine the long-term phosphorus concentrations of Sheridan Lake
- Determine the necessary phosphorus load reduction to achieve a TSI of 45
- Estimate time to reach TSI of 45 once load reductions begin

During the study period for the project, stream flow values were consistently below average. Lower stream flow potentially means less nutrient loading. A one-year picture of the lake could give misleading information about its actual state. A model that took into account the past variations in flow and concentration would provide for better nutrient loadings and lake response. Once the model was calibrated, it could be used to evaluate the level of phosphorus load reduction necessary to achieve a TSI of 45. The time to reach the lowered TSI is affected by nutrient feedback from lake sediments. This feedback can delay the effects of a reduced nutrient load and a model that could account for this and provide an estimated time of recovery was desired.

To accomplish the modeling objectives, a lake phosphorus model by Chapra and Canale (1991) was extensively modified. The model uses an Excel worksheet as the input and Visual Basic code to make the calculations. A daily time step is used for phosphorus calculations. It was set up to calculate phosphorus levels in four different parts of the lake: the epilimnion, hypolimnion, shallow sediments, and deep sediments. The complete code is contained in Appendix C. The basics of the model are shown in Figure 10.

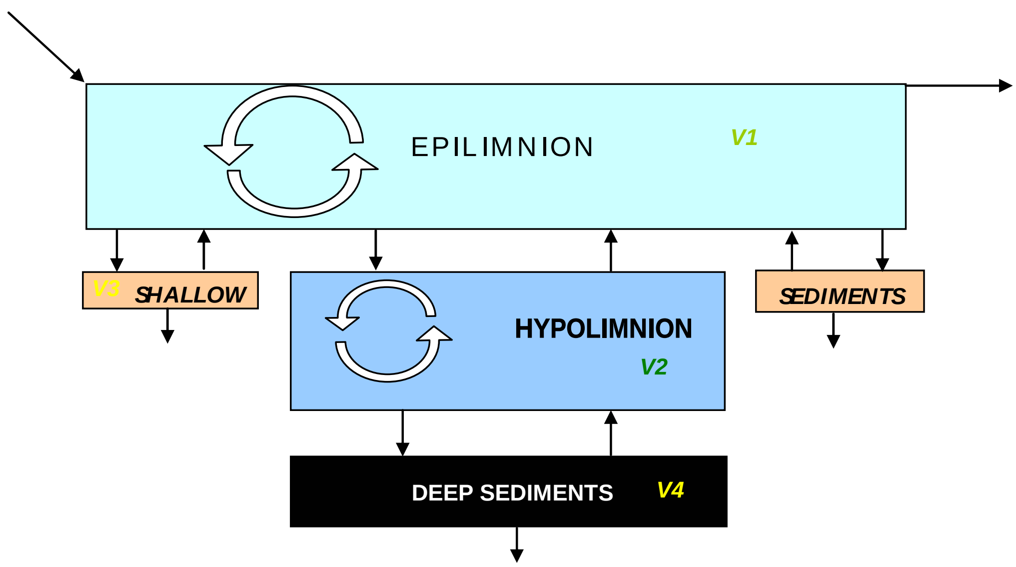


Figure 10. Basic Modeling Components, Arrows represent paths of phosphorus

The epilimnion is the shallow waters of a lake that remain well mixed throughout the summer when the lake becomes thermally stratified. Phosphorus enters the epilimnion throughout the year from incoming flow. The water that flows out of the lake carries phosphorus with it. While in the lake, phosphorus is subject to settling from the epilimnion to the hypolimnion or to the shallow sediments of the lake.

The hypolimnion represents the deeper waters of the lake that become separated from the epilimnion by a thermal barrier during summer months when the lake is stratified. The hypolimnion receives some of the phosphorus that settles out of the epilimnion. Wind mixing and diffusion can transfer phosphorus back to the epilimnion from the hypolimnion. Settling of phosphorus within the hypolimnion leads to a transfer of phosphorus to the deep lake sediments that underlie the hypolimnion. Phosphorus in both the shallow and deep sediments is subject to either burial by further settling or recycling back into the overlying waters. Shallow sediments are those in direct contact with the epilimnion while deep sediments are in contact with the hypolimnion. Each of the four components of the model are treated as being completely mixed on a daily basis.

A set of physically based governing equations was used to model the movement of phosphorus into, within, and out of the system. The equations for phosphorus are summarized as follows:

- Inflow = $Q*p_{in}$ where p_{in} is the incoming total phosphorus concentration
- Outflow = $Q*p_{ep}$ where p_{ep} is the epilimnion total phosphorus concentration
- Epilimnion Settling = $p_{ep}*V_s*(A_S + A_H)*NSRP$ where V_s is settling velocity, A_S is the surface area of shallow sediment, A_H is the epilimnion area in contact with the hypolimnion, and NSRP is the fraction of the phosphorus subject to settling. Epilimnion settling goes to both the hypolimnion and shallow sediments.
- Hypolimnion Settling = $p_H*V_s*A_H*NSRP$ where p_H is the concentration of total phosphorus in the hypolimnion.
- Hypolimnion Transfer to Epilimnion = $p_H*V_T*A_H$ where V_T is the transfer velocity of total phosphorus from the hypolimnion to the epilimnion
- Sediment Recycling = $V_r*A_S*P_S$ where V_r is the release velocity, A_S is the surface area of sediment, and P_S is sediment total phosphorus concentration
- Sediment Burial = $V_B*A_S*P_S$ where V_B is the burial velocity

Inflow and Outflow of Phosphorus

The incoming phosphorus enters the epilimnion with the inflowing tributary water. One of the user inputs on the Excel spreadsheet is each year's total flow volume and phosphorus concentration. Incoming phosphorus varies from year to year depending on flow and concentrations. The USGS gage on Spring Creek above Sheridan Lake was established and has kept a continuous flow record since October 1990. The USGS gage downstream of Sheridan Lake has continuous flow data back to 1987 and consistently has an average annual flow that is 30% higher than the gage above Sheridan Lake. This ratio between the two gages was used to estimate flow at the upstream gage back to 1987. To get a better feel for long term flow rates, the flow on Spring Creek was compared to the flow in Rapid Creek above Pactola. The USGS has operated a continuous flow gage at this location since October 1953. A map from the Black Hills Hydrology Study (2002) shows that both basins are located in the Central Black Hills and originate in the Madison Limestone. Comparison of yearly mean flow values showed that Spring Creek averaged 31% of Rapid Creek's flow during wet years and 16% of Rapid Creek's flow during dry years. It was assumed that Rapid Creek had more springs to keep flow up in dry years. The break point between wet and dry years was defined by an average annual flow of 40 cfs on Rapid Creek. The flow data for Spring and Rapid Creeks is shown in Table 8. With a relationship established between Spring Creek and Rapid Creek, an average yearly flow for Spring Creek could be estimated back to 1954. This was used to calculate a long term average flow for Spring Creek that could be used for estimating lake response in future years. This long term annual average flow rate came to 13.1 cfs and was also applied to the years 1940-1953 for modeling.

Table 8. Annual average flow values for Spring Creek and Rapid Creek and the flow ratio between them. 1987-1990 flows based on USGS gage 06407500

Year	Spring Creek (cfs)	Rapid Creek (cfs)	Ratio SC:RC
1987*	7.8	33.3	0.234
1988*	1.3	24.4	0.055
1989*	0.9	20.9	0.045
1990*	7.1	26.2	0.269
1991	23.2	46.7	0.497
1992	5.23	26.3	0.199
1993	27.3	64.4	0.424
1994	9.92	48.7	0.204
1995	39.9	88.5	0.451
1996	32.9	93.8	0.351
1997	43.3	137	0.316
1998	37.1	135	0.275
1999	43.8	125	0.350
2000	11.0	59.4	0.185
2001	11.1	45.5	0.244

To model the incoming concentration of total phosphorus, the FLUX program was employed. FLUX uses sample and flow data to calculate a relation between flow and concentration and applies this to a daily flow record to come up with annual loads and average concentrations. Current study samples and USGS samples from 1991-92 were used in estimating phosphorus loads and concentrations back to 1991. The average incoming total phosphorus concentration over this period was 90 mg/m^3 and was applied to the model back to 1973, the year Hill City installed its lagoons. Prior to 1973, the EPA estimated that Hill City was responsible for 465 kg per year of phosphorus entering Sheridan Lake through sewage discharge. An extra 465 kg per year distributed over 13.1 cfs translates to a total phosphorus concentration that was 40mg/m^3 higher. So prior to 1973, a phosphorus concentration of 130 mg/m^3 was used.

During the study it was noted that stream flow varies throughout the year according to the season. To incorporate the effects of seasonal differences, one of the user inputs on the Excel model is average monthly flow in cfs. The program uses this to determine the percentage of flow in each month. The USGS records provided the data for average monthly flow. Since the program works on a daily time step, the program keeps track of the day of the year. This is used to determine the month. The month's average percentage of the overall annual flow volume is taken times the current year's total flow volume. The program then divides this number by the number of days in the month to calculate the total daily flow volume. The input block for the program is shown in Table 9. Thus, in a given year, the flow for each day of the month is the same. The ratio of flow in one month to another is also always the same within a given year. The incoming phosphorus concentration is left the same throughout the year.

Outflow from the lake is the same as inflow. Since the primary outflow from Sheridan Lake is a surface spillway, the outflow concentration is that of the epilimnion. The model neglects precipitation, evaporation, groundwater, and the contribution of smaller tributaries to the lake such as Horse Creek and Calumet Creek. During the sampling period these tributaries were responsible for approximately 5% of the incoming phosphorus while Spring Creek provided the other 95%. In addition, there is no long term hydrologic or chemical data available for Horse Creek or Calumet Creek.

Table 9. Input block with USGS flow values

Division of Flow			
Month	Avg Q (cfs)	% of annual	days
Jan	6.52	***2.3%***	***31***
Feb	6.92	***2.2%***	***28***
Mar	12.4	***4.3%***	***31***
Apr	22.6	***7.7%***	***30***
May	61.2	***21.5%***	***31***
Jun	82.2	***27.9%***	***30***
Jul	32.5	***11.4%***	***31***
Aug	19.6	***6.9%***	***31***
Sep	12.2	***4.1%***	***30***
Oct	12.1	***4.2%***	***31***
Nov	12.6	***4.3%***	***30***
Dec	9.21	***3.2%***	***31***
Avg Yearly	***24.2***		

Settling and Mixing of Phosphorus

Settling of phosphorus from the epilimnion occurs in various ways. Plants and animals die and settle to the sediment. The transfer of nutrients to the sediment is not 100% from settling and with algae, most of the phosphorus is lost before it gets to the bottom of the lake (Wetzel, 2001). Phosphorus also tends to adsorb strongly to clay particles which are subject to settling. Wind can circulate lake waters and thus phosphorus. During sampling it was noted that the percent of total phosphorus that was ortho-phosphorus was at its lowest, approximately 10%, during the growing season. Models of phosphorus are often set so that only particulate phosphorus is subject to settling (Chapra, 1997). To model the settling of phosphorus, an apparent settling velocity is used that is not the true settling rate of phosphorus but most correctly models its removal from the modeling component. To account for particulate settling, the user inputs the NSRP (not soluble reactive phosphorus) for summer (May through October) and winter (November through April). The NSRP is that portion of the phosphorus that can settle and is the difference between the total phosphorus value and the ortho-phosphorus value. The model of Sheridan Lake used 90% NSRP in the summer and 50% in the winter to reflect the values found during sampling.

A lake phosphorus budget was developed to estimate a settling velocity for the model. By treating the lake as a completely mixed reactor, the paths of phosphorus can be simplified. Phosphorus enters the lake with tributary inflow and from the bottom sediments. It leaves through outflow and settling. First, months when the oxygen concentration of the hypolimnion was greater than 1.5 mg/L were considered separately. It was assumed that recycling of phosphorus from the sediment was minimal during these months and could be neglected. Incoming and outgoing phosphorus were estimated using available flow records and water quality records. The outflow of total phosphorus was subtracted from the inflow. The difference between the two is accounted for by the sediment. If recycling is minimal, then the difference can be attributed to settling. Settling mass is approximated by the settling velocity times area of settling times total phosphorus concentration of the water.

(5) $TP_{settle} = V_s A_s p$

The equation can then be solved for settling velocity. In Sheridan Lake, mass balance showed a loss of 860 kg of phosphorus over 194 days. The settling area was assumed to be the entire lake area, or 383 acres. The average phosphorus concentration over this period was 0.034 mg/L. By calculating the mass of phosphorus change, the surface settling area, and the phosphorus concentration, equation (5) can be solved for velocity. This velocity was then divided by the NSRP value of 0.5 that was reflective of average NSRP values throughout the lake to come up with settling velocity of 61 m/yr. The complete phosphorus and orthophosphorus values for the months used in the calculations are shown in Table 10. A value of 60 was used in the model. Since the calculations treated the lake as a complete mix, hypolimnion settling velocity was assumed to be similar to settling velocity in the epilimnion. The settling of phosphorus out of the hypolimnion works in the same way as the epilimnion. Data showed the percentage of ortho-phosphorus in the hypolimnion samples was much higher, so only 50% of the hypolimnion phosphorus was set to be subject to settling in the model throughout the year.

Table 10. Orthophosphorus levels during months used for settling

Station		Date	Total Phosphorus (mg/L)	Orthophosphorus (mg/L)	% Orthophosphorus
SL-1	Upper	7/10/02	0.016	0.002	13%
SL-1	Lower	7/10/02	0.041	0.041	99%
SL-2	Upper	7/10/02	0.015	0.002	13%
SL-2	Lower	7/10/02	0.017	0.006	35%
SL-1	Upper	10/21/02	0.034	0.016	47%
SL-1	Lower	10/21/02	0.040	0.021	53%
SL-2	Upper	10/21/02	0.043	0.023	54%
SL-2	Lower	10/21/02	0.340	0.308	91%
SL-1	Upper	2/18/03	0.026	0.016	60%
SL-1	Lower	2/18/03	0.042	0.032	77%
SL-2	Upper	2/18/03	0.036	0.019	52%
SL-2	lower	2/18/03	0.047	0.035	74%
SL-1	Upper	4/15/03	0.010	0.004	35%
SL-1	Lower	4/15/03	0.066	0.057	86%
SL-2	Upper	4/15/03	0.013	0.007	54%
SL-2	lower	4/15/03	0.036	0.030	83%
SL-1	Upper	5/7/03	0.017	0.004	21%
SL-1	Lower	5/7/03	0.031	0.014	45%
SL-2	Upper	5/7/03	0.035	0.022	63%
SL-2	lower	5/7/03	0.020	0.004	18%
SL-1	Upper	6/4/03	0.014	0.004	25%
SL-1	Lower	6/4/03	0.021	0.010	48%
SL-2	Upper	6/4/03	0.012	0.004	29%
SL-2	lower	6/4/03	0.038	0.032	84%

Table 11: Phosphorus Concentrations and Components from lower waters of Sheridan Lake

Site	Date	Total Phosphorus (mg/L)	Orthophosphorus (mg/L)	% Orthophosphorus
SL-1	8/14/02	0.15	0.128	85%
SL-2	8/14/02	0.29	0.240	83%
SL-1	9/24/02	0.28	0.240	86%
SL-2	9/24/02	0.35	0.336	96%
SL-1	10/21/02	0.04	0.021	53%
SL-2	10/21/02	0.34	0.308	91%

The area of settling for phosphorus from the epilimnion is equal to the lake surface area of 383 acres (1.55×10^6 m^2). Bathymetric data from the GFP(1986) was used to partition the epilimnion into areas that were subject to either settling of phosphorus into shallow sediments (6.6×10^5 m^2) or settling of phosphorus into the hypolimnion (8.9×10^5 m^2). The area of settling from the epilimnion into the hypolimnion is also used as the area for settling from the hypolimnion into the deep sediments.

For hypolimnion transfer to the epilimnion, there are a number of user inputs. The user picks four days of the year that correspond to melting of ice, onset of summer stratification, fall mixing, and the onset of ice and winter stratification. The transfer velocity between the hypolimnion and epilimnion has two different values that correspond to mixed and stratified periods. During the stratified summer period a strong thermal barrier slows transfer but does not completely stop it (Chapra, 1997). In addition, it was observed that the metalimnion progressed downwards over the summer, see Figure 4. The model was initially set with an apparent transfer velocity of 2 meters per year during stratification. During mixing, the transfer velocity was set equal to the settling velocity to try and achieve the effect of a well mixed lake. Both values were adjusted during calibration.

Movement of Phosphorus from Sediment

Phosphorus in the sediments can either be recycled to the overlying waters or leave the sediments by deep burial. As more particles settle to the bottom, phosphorus in the sediment becomes buried by enough overlying sediment to become effectively inactive (Wetzel, 2001). The model controls this with the user input burial velocity. Sediment data from DENR showed the depths of sediment in Sheridan Lake inlets. The data was collected in 2002 and showed there to be approximately 3 feet of sediment in the shallow areas and 1-2 feet of sediment in the deeper areas. Since Sheridan Lake was closed in 1940, this meant the present sediment took 62 years to accumulate. By dividing the depth by the time, an average burial rate was determined. The results are shown in Table 12.

Table 12. Calculations of sediment burial rates

	sediment depth (ft)	time (yrs)	ft/yr	mm/yr
burial-shallow	3	62	0.048	14.7
burial-deep	1.6	62	0.026	7.9

The release of phosphorus from the shallow sediments to the overlying epilimnion waters is controlled by user inputs. The inputs include a release velocity, a summer coefficient, and a winter coefficient so there will be different seasonal release rates. The summer coefficient is multiplied times the release velocity in the months of May through October with the winter coefficient being used the rest of the year. The logic is that rooted macrophyte growth is the main roadway for movement of phosphorus from the shallow sediments to the overlying water (Wetzel, 2001). An Elutriate test from the Spring Creek Inlet showed that simple mixing of sediment and water did not increase the phosphorus content of the water. This suggests that wind by itself is ineffective at transferring phosphorus. But the growth of plants and their consumption and decay would result in a transfer of phosphorus to the water. Since plant growth is primarily a summer process, the summer coefficient was set and left at 1 and the winter coefficient was left at zero. The daily mass movement of phosphorus from the sediment is a product of area, sediment phosphorus concentration, and velocity of burial or release. Burial rates remain the same throughout the year because there was no data to indicate how they might vary over the course of a year.

Within the hypolimnion, large reductions in summer oxygen levels corresponded to increases in phosphorus concentrations. A sharp decrease in phosphorus concentration within the hypolimnion was observed upon mixing and the return of oxygen in the autumn. There was no sharp rise in phosphorus concentration during the winter though there was some oxygen depletion in the waters immediately above the sediment. As was stated earlier, the critical level for release of phosphorus is thought to occur when the oxygen level in the hypolimnion drops below 1.5 mg/L. In Sheridan Lake the large increase in hypolimnion phosphorus concentrations occurred after the average oxygen level dropped below 1.46 mg/L. To model this effect, the user inputs an initial oxygen concentration for the hypolimnion in summer and winter, an average hypolimnion temperature for summer and winter, and a release velocity. Monitoring showed initial oxygen values to be 8.5 mg/L in the summer and 12 mg/L in the winter while the average temperatures were 9^{o}C and 4^{o}C, respectively.

Upon the user specified date for onset of stratification, depletion of oxygen in the hypolimnion begins. The rate of hypolimnetic oxygen demand is estimated by using an equation from Chapra(1997) that calculates it as a factor of average phosphorus concentration in the lake from the previous year. The equation reads:

(6) $AHOD = 0.086p^{0.478}$

where AHOD is the areal hypolimnetic oxygen demand in g/m^2-day and p is the total phosphorus concentration in mg/m^3. Dividing the AHOD by the hypolimnion thickness, in meters, gives an oxygen demand with units of g/m^3-day or mg/L-day. The temperature difference between winter and summer affects the oxygen demand in the winter. Winter demand is equal to summer demand except it is multiplied by 1.08 raised to the power of winter temperature minus the summer temperature. The equation is as follows:

(7) $WHOD = AHOD*1.08^{Tw-Ts}$

The average phosphorus concentration in Sheridan Lake during sampling was 41.4 mg/m^3. Using equation (7) this equals an oxygen demand of 0.085 mg/L-day. From May to July 2002 the average oxygen demand in the hypolimnion was 0.120 mg/L-day. Once the overall oxygen level reaches 1.5 mg/L, release of phosphorus from the sediments begins. The calculated mass of released phosphorus is equal to the product of sediment surface area, sediment total phosphorus concentration, and release velocity. Once turnover begins, all movement of phosphorus from the deep sediments to the hypolimnion is halted.

According to Wetzel (2001), at autumnal turnover, large amounts of phosphorus are precipitated after bonding to iron and manganese. To reflect this, the settling rate for phosphorus is multiplied by a factor of 8 for the first ten days after mixing. This factor reflects actual field conditions. As oxygen levels increased in the hypolimnion in October, phosphorus concentrations dropped precipitously. The mass calculation for burial of deep sediments is represented the same as the shallow sediment calculation.

Model Calibration

The forcing functions of flow and concentration were based on this study's water quality monitoring results and previously collected data. Where possible, physical parameters such as the settling of phosphorus were solved for in a numeric fashion using the collected data. Values that could not be solved for were adjusted in an effort to match observed levels of phosphorus in the lake. The model summarized the phosphorus levels for each of the four components of the system. The average phosphorus concentration value is then found at the end of each year. The collection of water samples from

Sheridan Lake was done on a monthly basis from May 2002 until June 2003 with the exception of November and December 2002. This was the only year long set of data available so 2002 was the year used for calibration. The average water phosphorus concentration values toward which the model was calibrated are actually averaged over the study period, but the majority of the data was collected in 2002. The only sediment samples collected and analyzed directly for phosphorus content were collected in August 2003. To calibrate the model towards these values, the phosphorus values for individual days were output to allow a direct comparison. The values adjusted during calibration were sediment release velocity for the shallow and deep sediment, and the transfer velocity of phosphorus from the hypolimnion to the epilimnion. The calibrated and measured values are shown in Table 13.

Table 13. Modeled versus measured phosphorus values

Model Component	**Model Values**	**Field Values**	**units**
Epilimnion	26.4	26.7	mg/m^3
Hypolimnion	85.1	65.5	mg/m^3
Shallow Sediments	136	140	mg/kg
Deep Sediments	186	180	mg/kg

Good correlation is evident for phosphorus concentrations in the epilimnion, shallow sediment, and deep sediment. Although the hypolimnion value appears to be high, the phosphorus concentration within the hypolimnion can vary significantly and field values were based on only a surface and bottom sample.

Model Verification

To check the model, a mass balance analysis was done. The phosphorus entering the overall system was the inflow times the concentration. The phosphorus leaving the system was through outflow and burial. Over the long term there should be little difference between the overall amounts of phosphorus entering the lake and leaving the lake and accumulating in the sediments. To view the results, a function was added to the program to sum the inputs and outputs for each day of the year and report them to the output worksheet. A graph of the changing phosphorus flux is shown in Figure 11.

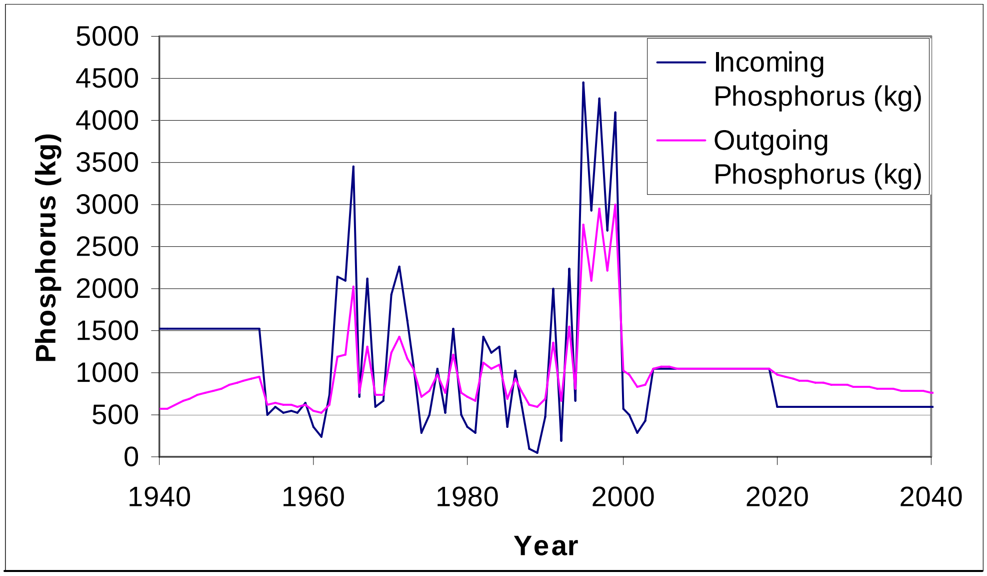


Figure 11. Annual incoming and outgoing phosphorus loads for Sheridan Lake

The model was run between 1940 and 2040 to check for mass balance. The overall incoming load was approximately 111,000 kg while the outgoing load was 99,000 kg. The increase in lake water and sediment phosphorus was 12,000 kg. Essentially the model accounted for all the phosphorus with minimal error.

Phosphorus Load Reductions

To determine the long term conditions of the lake, the calibrated model was run into future years with average flow volumes (13 cfs) and present phosphorus loading concentrations (90 mg/m^3). With constant inflows, the phosphorus concentrations in the lake would approach a steady state concentration that reflects the long term reaction of the lake to the current loading conditions. Also, with constant loading the incoming and outgoing phosphorus levels will approach equilibrium. With the current loading, the long term phosphorus concentration of the epilimnion was modeled to be approximately 33 mg/m^3 which represents a TSI of 54.6.

In order to reach a TSI value of 45, phosphorus concentrations in the epilimnion would need to be reduced to 17 mg/m^3. In order to determine the necessary reduction in phosphorus loading, new incoming phosphorus concentration values were entered and the model was run until steady state was reached. It is predicted that the average incoming phosphorus concentration would need to be reduced to 50.9 mg/m^3 in order to have the average epilimnion concentration be 17 mg/m^3. This would be a 43% reduction from the current average concentration of 90 mg/m^3. This reduction is represented as a reduction in the loading from Spring Creek. Since phosphorus values provided higher TSI calculations during the study, there is an inherent margin of safety in using phosphorus as the indicator for TSI.

The time to reach a lower TSI is dependent on the incoming concentration and the volume of flow. To estimate the time of recovery, the average yearly flow volume was used. Since the final steady state can take many decades to reach, the time results were analyzed for different percent recoveries. A 50% recovery is halfway towards the final concentration and TSI goal, or with a starting epilimnion phosphorus concentration of 33 mg/m^3, 50% recovery is a concentration of 25 mg/m^3. The model showed a 50% recovery after 5 years, 70% after 18 years and 90% after 55 years.

PHOSPHORUS LOADS AND LOAD ALLOCATION

Proposed Phosphorous Load Reductions Along Spring Creek

In order to reduce the phosphorus load from Spring Creek, it is necessary to know where the phosphorus load is generated within the watershed. Modeling of phosphorus loading along Spring Creek above Sheridan Lake looked primarily at three different sections. These were below Mitchell Lake, Mitchell Lake, and above Mitchell Lake. The reason is that Mitchell Lake acts as a large sink for phosphorus that removes pollutants from Spring Creek. Within these three regions are smaller reaches identified by the monitoring stations that were placed along the creek. These reaches and the accompanying watersheds are shown in Figure 12.

The station just above Sheridan Lake is SCT-1. Just below Mitchell Lake was a station identified as SCT-2. Palmer Creek upstream of the junction with Spring Creek is identified as PCT-1 and above the KOA campground is identified as PCT-2. Upstream of Mitchell Lake, SCT-4 is Spring Creek below Hill City, SCT-5 is just upstream of the Hill City lagoons, and SCT-6 is upstream of Hill City. NCT-1 is Newton Fork Creek below Major Lake in Hill City shortly before it connects with Spring Creek. SCT-7 was sited on Spring Creek near the northern entrance to the Rafter J Campground, just below the confluence with Sunday Gulch. Sunday Gulch was monitored from SGT-1, just downstream of where it crosses Highway 385. SCT-8 was at the initial junction of Spring Creek and Spring Creek Road. Modeling of the individual monitoring locations along Spring Creek was done using the FLUX (Walker 1996) program in the same manner as modeling of phosphorus loading to Sheridan Lake.

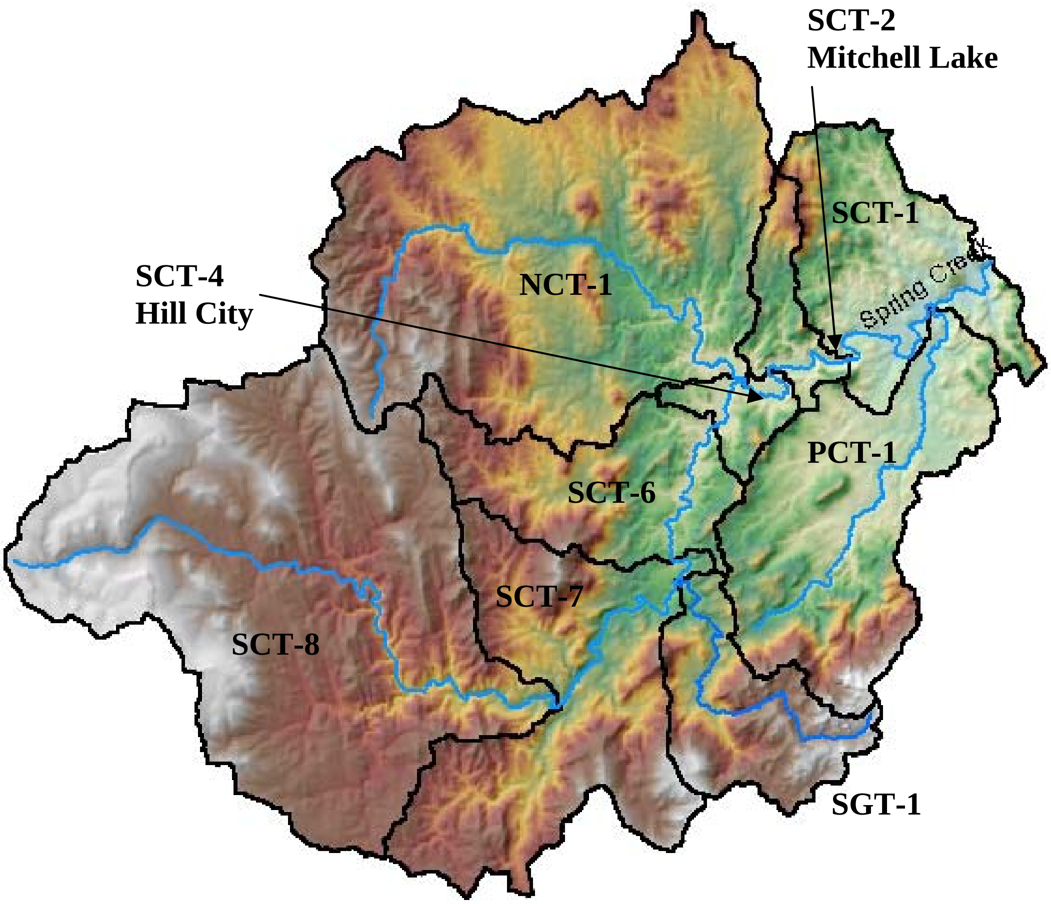


Figure 12. Spring Creek above Sheridan Lake Basin is broken into sub-basins for phosphorus loading analysis. Stations listed are representative of sub-basin's downstream monitoring station

Lake modeling indicated that a 40-50% reduction in incoming phosphorus would be necessary to lower the TSI value of Sheridan Lake to 45. Thus, it becomes necessary to determine where the current load is coming from and to assign potential load reductions. One assumption is necessary; that the percentage contribution of phosphorus from different sources will be similar from year to year. All modeling was based on flow and concentration data collected from Spring 2002 until Summer 2003. All calculated loads and loads referred to in the following discussion are annual loads.

Sheridan Lake has three major tributaries, Spring Creek, Horse Creek, and Calumet Creek. FLUX modeling showed minimal (less than 5%) phosphorus inputs from the latter two sources with Spring Creek accounting for over 95% of the tributary inflow of phosphorus.

From Sheridan Lake to Mitchell Lake

Modeling indicated an annual input of 437 kg of phosphorus from Spring Creek to Sheridan Lake. The load at SCT-2 was 293 kg, leaving an increase of 144 kg between Mitchell Lake and Sheridan Lake. Of this 144 kg increase, Palmer Creek was modeled to contribute 113 kg, with the other 31 kg coming from other non-point sources. The 31 kg is thought to originate almost entirely during storms. Comparisons of base flow samples showed SCT-1 to consistently have a similar or lower concentration of total phosphorus than SCT-2. One of the most important keys to phosphorus transportation is erosion (Olem and Novotny, 2001). Phosphorus tends to bond tightly to sediment. Therefore the erosion and movement of sediment corresponds to the movement of phosphorus. This means that the closer the sediment is to the creek, the more likely it will carry phosphorus into the creek during runoff events.

Between SCT-1 and SCT-2, there are varied potential sources of sediment close to the creek. Pastures with grazing animals can be a source of phosphorus in three major ways. The first is direct deposition of waste into the creek. The second is overgrazing; pastures with little grass cover are much more susceptible to erosion and the transport of phosphorus. The third is through bank destabilization. When cattle and horses spend time on the banks of the creek, they can trample vegetation and leave more sediment free to erode during high flows and runoff events. Removing some animals or providing additional forage can remedy overgrazing. Proper range management has been shown to reduce phosphorus input by up to 80% (Novotny and Olem, 1994). The direct deposition of waste and bank destabilization are both results of the same condition, animals spending time in the creek. Fenced management zones next to the creek would only be subject to grazing for short periods of time. Such buffers have been shown to reduce phosphorus loads by 50-90% (Novotny and Olem, 1994). However, this is expensive and an alternative is providing another source of water away from the creek. This provides livestock a place to drink besides the creek and case studies have had reductions in phosphorus loading of 81% (Ritter and Shirmohammadi, 2001).

Near the lumber mill, approximately 1.5 miles downstream of Mitchell Lake, there are tracts of exposed soil next to the creek. Sampling showed this reach to contribute significant amounts of suspended sediments, nitrogen, and phosphorus during runoff events. The complete results from these samples are shown in Table 14. Both samples were collected from turbulent water during or immediately after runoff producing storm events. The upstream site was near the culvert immediately before Spring Creek enters the lumber mill. Vegetative filter strips next to the creek could slow the water and force some sediments and nutrients to drop out. In urban environments, these strips next to pavement can reduce phosphorus loading by 40-60% during runoff events.

Table 14. Comparison of storm samples from just above and below the lumber mill. The percent increase is the increase at the down stream site (SCT-1A).

Station	Upstream of Mill at culvert	SCT-1A	Units	% Increase
Date	6/12/2003	6/12/2003		
Time	21:00	20:50		
E-coli	4	40	col/100 mL	900%
Fecal	48	>1600	CFU/100 mL	
Alkalinity	110	390	mg/L	255%
Total Solids	260	1100	mg/L	323%
TSS	56	830	mg/L	1382%
Ammonia	0.025	0.1	mg/L	300%
Nitrate/trite	0.07	0.25	mg/L	257%
TKN	0.78	2.6	mg/L	233%
Orthophosphorus	0.04	0.45	mg/L	1025%
Total Phosphorus	0.07	0.73	mg/L	943%
Date	8/7/2003	8/7/2003		
Time	18:25	18:25		
E-coli	670	12000	col/100 mL	1691%
Fecal	>16000	>16000	mpn/100 mL	
Alkalinity	130	380	mg/L	192%
Total Solids	360	1300	mg/L	261%
TSS	120	930	mg/L	675%
Ammonia	0.08	0.17	mg/L	113%
Nitrate/trite	0.29	1.2	mg/L	314%
TKN	1.2	2.9	mg/L	142%
Orthophosphorus	0.11	0.48	mg/L	336%
Total Phosphorus	0.18	0.8	mg/L	344%

All samples are grab samples
Both sets were collected during storm events

Another option would be some form of storm water detention. Dry detention is where ponds hold water only after runoff events and discharges over approximately 12 hours. These can reduce phosphorus loading by 10-40% with 25% as the recommended value (ASCE 1998). Wet detention ponds are those that maintain a permanent pool of water and use long hydraulic residence times to allow chemical and biological, as well as physical activities to strip nutrients out of the water. Well-maintained ponds can cut phosphorus loading by 50-60% (ASCE 1998). Other types of ponds involve infiltration of retained storm water. It is recommended that there be at least two feet of difference between the bottom of the pond and the seasonal high water table. Infiltration ponds can be by themselves, or operate in cooperation with dry or wet ponds with the infiltration ponds catching the "first flush" that is normally highest in nutrients. These combinations can lower phosphorus loading by 60-100% (ASCE 1998). Even small infiltration ponds that only catch the runoff from a 2 yr 24 hour storm can remove approximately 80% of the annual suspended solids load and with it high amounts of phosphorus (MPCA, 2000). Maintenance of clean, high permeability filter material is of the utmost importance. Other potential sources of phosphorus include yard runoff, septic tanks, and natural inflows. None of these sources was shown to be important but none can be eliminated either. Septic loads are very difficult to gage and have the potential to be very low due to filtering by the soil (Chapra and Reckhow, 1983).

Using midrange estimates for percent phosphorus removal of 64% and assuming the entire 31 kg can be potentially removed, an estimated load reduction potential of 20 kg is calculated for this reach. This leaves an allowable load of 11 kg.

Palmer Gulch Creek

Palmer Creek flows into Spring Creek between SCT1 and SCT2 and consistently had the highest nutrient concentrations throughout the study. Although the flow is a small part of the Spring Creek discharge, its phosphorus load represents 26% of the total load entering Sheridan Lake and 76% of the increase in load downstream of Mitchell Lake. During storms the Palmer Basin reacted quickly and produced water highly concentrated in phosphorus including grab sample values of 1.5 and 2.8 mg/L and a composite value of 0.98 mg/L. This is in stark contrast to the average SCT-1 concentration of 0.051 mg/L. Palmer Creek has large campground areas near PCT-2 that provide space for thousands of campers during a typical summer. This use of land also provides areas of low permeability very close to the creek that increase storm water runoff. Horse stables are located very close to the creek and horse trails run close to the creek in numerous places. All along the creek there are instances of bank sloughing. Palmer Creek appears to have unstable banks which can lead to erosion and phosphorus loading during high flow and runoff events. The conditions along the banks appear in many places, regardless of where livestock are which indicates that high flows from storm water runoff are a potential cause of bank erosion. There are a number of cattle that graze pastures along the creek.

Potential reductions in the basin could logically start with stream bank stabilization. Efforts towards stabilization can be done with riprap or dense vegetation such as well-rooted grasses and willows. A study of bank erosion of cohesive material showed that banks with well developed root networks have three times the critical shear stress of banks with weak under developed vegetation (Millar and Quick, 1998). Stabilized banks have shown phosphorus load reductions of 50-70% (Novoty and Olem, 1994). Alternate water sources for cattle could reduce in-stream animal time and help with the stabilization in grazed areas as well as work to reduce direct deposition. Keeping horse trails away from the creek, where possible, would help in allowing denser vegetation to flourish. This vegetation would also act as a filter strip during runoff events.

At the campgrounds detention/retention basins in combination with filter strips could be used to filter out nutrients. In addition this would slow the entrance of water to the creek during runoff events and lower the peak flow. This could further help in reducing the erosion of stream banks. Another possibility for campground detention is filter trenches. These are trenches lined with filter fabric and backfilled with stone. Runoff is directed over grass strips before entering to reduce the solids load. They can reduce phosphorus loading by 50-75% (ASCE 1998). Thicker vegetative strips along the creek could reduce inflow during runoff events and help to stabilize stream banks.

Modeling indicated that 58% of Palmer Creek's load was due to runoff events. Storm water controls such as detention/retention, filter strips, and riparian zone management through stabilized banks with vegetative controls and off creek cattle watering could help reduce this load. In addition, more stable banks would keep sediment out of the water during base flow conditions also. Using estimates of 60% reduction of storm loads and 30% reduction of base loads would give a total reduction of 47%. This results in a load allocation of 60 kg of incoming phosphorus from Palmer Creek.

Much of the basin in this area is zoned for residential use. With increasing housing development, increases in impervious area can lead to larger, faster runoff during storms. Future development should make plans for managing the quantity and quality of storm water. Preparation of a stormwater master plan for this area is recommended.

Mitchell Lake upstream to SCT-4

The primary feature within this reach is Mitchell Lake, which acts as a large wet retention facility. This reach of the creek represents a sink zone for phosphorus. Modeling showed a lowering of the phosphorus load by 57% between SCT-4 and SCT-2. Current and proposed load estimates incorporate this removal. The slower moving water allows for attached nutrients to settle out with the sediment and for biological uptake by algae that are also subject to settling. Dredging of Mitchell Lake would increase the volume and the corresponding hydraulic residence time. This could allow for higher removal efficiency. It is worth noting that modeling was done using flows from Spring 2002 to Summer 2003. Precipitation and corresponding stream flow for much of the study time were below average. During wetter years, a higher flow would reduce the hydraulic residence time of Mitchell Lake and potentially its efficiency for removing phosphorus. In addition, during base flow conditions, phosphorus concentrations were consistently higher just downstream of Mitchell Lake than just upstream. This is an indication that some nutrients were reintroduced to the water after initial deposition primarily during base flow. Upstream of Mitchell Lake the channel appears to be fairly stable and lined with cobble and rock. There are some signs of previous bank instability, likely due to rerouting of the channel for road construction. There are also numerous homes close to the banks. One of the main factors affecting nutrient movement from septic tanks to surface waters is proximity (Chapra and Reckhow, 1983). In addition, roofs represent impervious areas and can increase peak flows and erosion if there is a direct flow path from the roofs to the creek.

The proposed future condition for Mitchell Lake is that it will continue to act as a large wet retention pond. Removal of sediments by dredging or a combination of draining, drying and excavation is recommended. With sediment removal an average phosphorous load reduction of 57% is assumed which is reflective of Mitchell Lake's efficiency of phosphorus removal during the monitoring period, May 2002 to June 2003.

Spring Creek through Hill City

This reach was the largest contributor of nutrients to Spring Creek during the study and as such should receive most of the attention for potential phosphorus reduction. Modeling showed an increase of the total phosphorus load from 315 kg (SCT6 above Hill City) up to 685 kg (SCT4 below Hill City), an increase of 370 kg. Large impervious areas are directly connected to Spring Creek through surface runoff and storm sewers. During rainstorms runoff from these areas quickly delivers nutrients to the creek. There is a range of potential options for storm water treatment. Starting at the source, filter strips could be used. Storm water from impervious areas would be directed across the vegetative strips to reduce the nutrient load before entering storm sewers. Inlet devices at storm sewer entrances could be used to trap sediments, trash, and organic waste such as leaves and grass. These can catch large amounts of nutrients but must be cleaned regularly and because of this have high maintenance costs. Baffle boxes within storm sewer pipes can remove up to 30% of the total phosphorus (ASCE 1998). Storm water could further be cleaned by redirecting it to detention, retention, or infiltration ponds. There are some issues with various detention type facilities. The first is space. Ponds require space at the lower end of a basin before it enters the creek. Dry detention pond bottoms should be located at least one foot above the seasonal high water table to prevent them from becoming infested with cattails. Wet detention ponds need to be cleaned regularly to maintain volume and also need to be managed so they do not become breeding grounds for mosquitoes. Infiltration ponds need to be at least two feet above ground water and should be an equal height above bedrock to maximize infiltration. In addition, infiltration ponds need to be periodically cleaned to maintain infiltration and volume capacities. Care should be taken when locating such ponds close to houses as they can raise the groundwater table and lead to flooded basements (ASCE 1998). Future construction work could incorporate low impact development. This includes structural changes such as using pervious pavement and hydraulic changes such as directing runoff from impervious areas over vegetated pervious areas. For instance, all houses could direct roof and driveway runoff onto lawns instead of into the street.

Newton Fork Creek enters Spring Creek at the lower end of Hill City and with it a phosphorus load. Modeling showed it to contribute only 53 kg of the 370 kg increase. Just before entering Spring Creek, Newton Fork passes through Major Lake. Major Lake acts much like Mitchell Lake in serving as a wet detention pond to remove nutrients during storm flows. Nutrient loads upstream of Major Lake could be reduced in some ways. Off creek watering of cattle and horses has some potential as does better vegetation along the banks. Overall the highest loads come during intense storms that carry sediment into the creek and have sustained high flows to push it through Major Lake. Here, like Mitchell, dredging or some form of sediment removal is recommended.

Within Hill City, there is usually grass along the creek that should serve as a good filter during runoff. Maintenance and improvement of this barrier could only help in reducing phosphorus loads and stabilizing the banks. The lagoons that store wastewater were not shown to be a significant source of phosphorus, but modeling does indicate that they contribute to the nitrogen load. Modeling showed a base load increase of 3 kg of phosphorus versus a nitrogen increase of 568 kg. This amounted to increases of 1.3% and 24% respectively. The estimated potential phosphorous load from lagoon seepage is within the margin of error of the analysis, while the nitrogen load is a clear indication of the connection.

Of the 685 kg of phosphorus passing SCT-4, modeling showed 67% of it to be due to storms and snowmelt. Clearly, storm water treatment could considerably reduce phosphorus loading. Using various storm water treatment alternatives identified previously, treating 80% of the runoff and removing 67% of the phosphorus could reduce the phosphorus load by 169 kg. Estimating a 30% load reduction from improvements to Major Lake and suggested measures in the Newton Fork watershed would remove another 16 kg from the total load. This combination would reduce the total load increase through Hill City from 370 kg to 185 kg, a 50% reduction.

Hill City is planning to build a wastewater treatment facility that will discharge to Spring Creek. The ultimate loading from the facility is expected to reach 45.4 kg of phosphorus per year. This load would occur regardless of hydrologic conditions so its effects would be of less importance in wet years and of higher importance in dry years.

The location of discharge from the facility has been considered at two different locations, the Palmer Creek Drainage and into Spring Creek above Mitchell Lake. Since Mitchell Lake acts as a large wet pond and removes phosphorus from Spring Creek, it would be more beneficial to have the load added to Spring Creek.

Upstream of Hill City

Above Hill City (above SCT6) and below SCT-7, the land along Spring Creek and its tributaries is used for a variety of purposes including housing, horse and cattle grazing, campgrounds, bike trails, highway department storage, and commercial storage. The banks appear stable in most places and much of the pastureland is not heavily grazed, leaving enough grass to slow runoff and provide filtering action. The main load increase appears to be due to increased flows of similar concentration from springs and tributaries. Thicker vegetative barriers along the creek in some places could act as filters and reduce loading during runoff events. Vegetative barriers would also help to stabilize banks in places where it shows signs of erosion. For the entire length of Spring Creek upstream of Hill City, modeling shows that runoff events are responsible for approximately 50% of the phosphorus load. Most BMP’s would serve to reduce this portion of the load. Others that could be implemented include pasture management on those areas that are currently overgrazed and off creek sources of water for livestock. With a combination of vegetative filter strips, bank stabilization, off creek water sources, and range management, an estimate can be made of reducing 60% of the storm load increase. This corresponds to a 30% reduction in the overall phosphorus loading along this stretch of Spring Creek. The current increase from SCT-7 to SCT-6 is estimated to be 81.3 kg. The reduction would lower the total input to 57 kg. Potential campground sources such as phosphorus detergents, pets, and on site waste represent uncertainties that cannot be accurately modeled but could be addressed through education and improved management practices.

SCT-7 to SCT-8

The modeled phosphorus increase for this reach was estimated to be 152 kg. Of that, Sunday Gulch is estimated to contribute 113.7 kg, or 75% of the increase. Sunday Gulch water samples consistently had high phosphorus content and high percentages of orthophosphorus. The Sunday Gulch Basin is predominantly Federal or State land. There are a number of houses and seasonal cabins close to the creek that could potentially contribute through septic systems. Forest Service GIS data showed 21 septic tanks in the Sunday Gulch Basin and all were located close to the creek. It was noted that Sunday Gulch water samples were consistently low in solids and very clear. In addition the banks appeared well vegetated and stable. Erosion and sediment contribution is most likely due to the steep topography of the basin and the channel. A possible source of phosphorus is Sylvan Lake. Located approximately 4 miles up Sunday Gulch, Sylvan Lake has shown high phosphorus concentrations over the last year during sampling and is currently being studied by the DENR.

Along this reach of Spring Creek (SCT8 to SCT 7) many riparian areas are well vegetated with dense stands of willows and other trees. Among the land that is used for grazing, off creek water was identified as a potential way to reduce phosphorus loading. Spring Creek is deeply entrenched in places and where cattle enter the water to drink, they tend to trample the banks and free up sediment for transport. This was noted on State GF&P land near SCT-8. Reinforcing popular crossing points with concrete pads could help reduce erosion as pastures often straddle the creek and cattle need access to both sides.

Until sources of phosphorus are more positively identified, no estimate can be made on potential phosphorus reductions in Sunday Gulch, but treatment of Sylvan Lake could help reduce the phosphorus load from Sunday Gulch. Inspection of septic systems in the Sunday Gulch Basin is recommended. Cattle crossings and off creek sources of water are the main BMP's for reduction of the increase between SCT-8 and SCT-7. These measures would help protect the riparian zone along the creek. Assuming a 50% reduction of incoming phosphorus, the load excluding Sunday Gulch would be reduced to 19 kg.

Above SCT-8

The upper reaches of Spring Creek had very low phosphorus concentrations during base flow conditions, averaging 0.017 mg/L. The high concentrations and corresponding loads came during intense storms that introduced sediments and nutrients to the creek. Much of the land higher in the watershed is publicly owned and used for grazing and logging. Once again off-creek sources of water could help as well as development and maintenance of a riparian buffer. Also, keeping erosion in check from dirt and gravel roads that run near the creek and its tributaries to a minimum would improve the water quality during runoff events. Modeling showed runoff events to be responsible for 55% of the total phosphorus load at SCT-8. If 60% of this could be controlled through BMPs, it would result in a reduction of 27 kg.

Summation of Phosphorus Reductions

Overall phosphorous load reductions have been based on percent reductions for various BMPs as presented in the literature. Average values from literature for percent load reductions have been assumed.

Upstream of Mitchell Lake the phosphorous load can be reduced from 684 kg/yr to 474 kg/yr for an overall reduction of 31 percent without load reduction in Sunday Gulch. There is currently uncertainty in identifying the phosphorus sources in Sunday Gulch. Including a potential reduction of 50% in the Sunday Gulch phosphorus contributions would reduce the phosphorus load above Mitchell Lake to 417 kg/yr for a reduction of 39 percent. This load is then further reduced as it goes through Mitchell Lake. Using an average load reduction of 57 percent through Mitchell Lake reduces the upstream loading to 179.5 kg/yr (this would represent the loading at SCT2). These loadings include the future inputs from the proposed waste water treatment plant.

Reduction of the phosphorus load contribution below Mitchell Lake is projected to be 50.6 percent, reducing the load from 144.2 kg/yr to 71.2 kg/yr. This includes a 47 percent reduction in load from Palmer Gulch and 64 percent reduction along Spring Creek between SCT1 and SCT2.

Thus, including Mitchell Lake and Sunday Gulch load reductions the total phosphorus load to Sheridan Lake from Spring Creek is reduced from 437 kg/yr to 251 kg/yr for an overall reduction in the phosphorus load from Spring Creek to Sheridan Lake of 43 percent. This is an overall reduction of the tributary phosphorus load to Sheridan Lake of approximately 40 percent. A summary of current and proposed phosphorus loads and locations is shown in Table 15.

TMDL Summary

Potential phosphorus reductions concentrated on four different areas:

- Land with large areas of impervious surfaces such as Hill City and the lumber mill.
- Land along the creeks with grazing
- Unstable stream banks
- Homes near the streams

Improvement in these areas can lower the input of phosphorus to Spring Creek and Sheridan Lake. Impervious areas should concentrate on catching the initial storm runoff with small filtration ponds that will not demand much area. Grazing land along the creeks should have sources of water away from the creeks and fortified crossing areas to minimize bank erosion. The unstable banks of the creek could be best served by riparian areas that provide living erosion control and a filter to slow the runoff of storm pollutants into the waters. Homes near the creek should have their septic tanks inspected.

Sheridan Lake

Sources	*Loads*	*% of Total Sheridan Load*	*Proposed Load Allocation*	*% reduction*	*Comments*
Calumet Creek	4	0.9%	4	0%	Minimal portion of load
Horse Creek	18.7	4.1%	18.7	0%	Water quality already good
Spring Creek	436.9	95.1%	250.9	43%	Main source
All Tributaries	459.6	100%	273.6	40.5%	

Spring Creek

Below Mitchell Lake *Sources*	*Load*	*% of Total Sheridan Load*	*Proposed Load*	*% reduction*	*Comments*	*Methods*
SCT-2 to SCT-1	31.2	6.8%	11.2	64%	Mostly event loaded	Detention, filter strips, off creek water, range management
PCT-1	113	24.6%	60	47%	Very high concentrations Event Driven	Off creek water, range management, detention/retention, infiltration, bank stabilization, manure control, filter strips
Mitchell Lake	-392.3		-238.1	39%	Will be treating less	Dredge Lake to increase volume and hydraulic residence Goal is to maintain phosphorus removal efficiency at 57%

Above Mitchell Lake *Sources*	*Load*	*% of Total Sheridan Load*	*Proposed Load*			
Hill City NPS	316.8	29.5%	147.8	53%	Largest source	Detention/retention, infiltration, source controls, filters
Newton Fork	53	4.9%	37	30%	Major Lake acts to clean	Off creek water sources, vegetative buffer/filter strips
SCT-7 to SCT-6	81.3	7.6%	57	30%	Most increase due to higher flow	Off creek water, bank stabilization, range management
Sunday Gulch	113.7	10.6%	56.7	50%	Unknown source, but important	Treat Sylvan Lake
SCT-8 to SCT-7	38.6	3.6%	19.3	50%	Event loading	Off creek water, bank stabilization, cattle crossings
Above SCT-8	81.6	7.6%	54.6	33%	Event loading	cut road erosion, off creek water sources
Hill City WWTP	0	0.0%	45.4		proposed loading	

Table 15. Summary of current and proposed phosphorus loading to Spring Creek

Uncertainties

It is unknown how long or at what amount storm flows affect base flow nutrient concentrations. Runoff loading could be an even larger portion of the flow than modeled. Over an annual basis streams will not retain phosphorus, but accumulations of phosphorus can develop and be exported during high flow events (Wetzel, 2001). Two areas of the Spring Creek Basin that consistently showed the highest phosphorus concentrations were Sunday Gulch and Palmer Creek. These two basins serve as the major drainage for the Harney Peak Area. Both have similar geology, steep drainages, and steep channels. The high concentrations could potentially be more natural than is suspected and as such would be difficult to remove. Finally, loading calculations, the proposed reductions, and allowable loads were all based on flows and samples taken during the project study period. Although the current stream flow record only goes back to 1990, it was thought that the flows and nutrient concentrations were lower during the study period than on average. In a wetter year with more stream flow, it is assumed that the overall phosphorus loads would be higher, but loading from each sub-basin would remain proportionally the same.

SUGGESTION FOR FUTURE ANALYSIS

Many assumptions were made concerning the movement of phosphorus within Sheridan Lake. Future monitoring could try to address some of these. Periodic sediment sampling could gage the movement of phosphorus to and from the sediments. Profile sampling could provide a more accurate estimate of the total phosphorus within Sheridan Lake.

CONCLUSION

Monitoring showed Sheridan Lake to have an average phosphorus TSI of 47.9 during the study period. The average TSI for secchi disk and chlorophyll-a were lower at 40.3 each. Flows into Sheridan Lake from Spring Creek were below average during the study period. This resulted in lower phosphorus loading to Sheridan Lake and likely resulted in lower TSI calculations. TSI calculations for chlorophyll-a ranged up to 51.6 during the growing season while the phosphorus TSI was 56.8 during October when Sheridan Lake was near turnover.

FLUX modeling showed Spring Creek to contribute 437 kg/yr of phosphorus. Hill City was the largest contributor of phosphorus with Palmer Creek and Sunday Gulch being important secondary sources. Impervious area near the creeks and soils prone to erosion along the creeks were the chief supplies of phosphorus. In both cases the movement of phosphorus was observed to enter the creeks by attachment to sediments. Erosion is made worse by cattle grazing and lack of riparian vegetation which serves to stabilize the stream banks.

A model of Sheridan Lake was developed to determine necessary phosphorus load reductions. The model showed that phosphorus loading would need to be reduced by 43% in order to achieve a TSI of 45. Time to recovery would proceed quickly at first with the model predicting a 50% recovery after 5 years of reduced phosphorus loading. However, a 70% recovery will require 18 years while the model shows that a 90% recovery will take 55 years. Reducing the phosphorus load will primarily require storm water management and erosion control. Methods include detention and infiltration ponds, grazing management, off creek sources of water for livestock, bank stabilization, and riparian zone management.

REFERENCES:

American Society of Civil Engineers. Urban Runoff Quality Management, ASCE Manual. Virginia: ASCE, 1998.

Bell Galyardt & Associates, Inc. Water Quality Parameter Update for 208 Area Wide Water Quality Management Planning Program. Sixth District Council of Local Governments South Dakota. Rapid City, SD, 1981.

Carter, Janet M., Driscol, D. G., & Williamson, J.E. 2002. The Black Hills Hydrology Study, South Dakota: U.S. Geological Survey Fact Sheet FS-046-02, 6p.

Chapra, S. C., & Canale, R. P. "Long-term phenomenological model of phosphorus and oxygen for stratified lakes." Water Res., 25, 707-720, 1991.

Chapra, S.C. & Reckhow, K. H. Engineering Approaches For Lake Management, Volume 2: Mechanistic Modeling. Boston: Butterworth Publishers, 1983

Chapra, Steven C., Surface Water-Quality Modeling. Boston, MA, WCB McGraw-Hill, 1997, p 844.

Cooke, G. D., Welch, E.B., Peterson, S.A., & Newroth, P.R. Lake and Reservoir Restoration. Boston: Butterworth Publishers, 1986.

Harms, L.L., Pirner, S. M., Baumen, S. J., & Henriksen, P.L. An Inventory of Eutrophic Lakes in Western South Dakota. South Dakota Department of Water and Natural Resources: Pierre, SD, 1981.

Khan, A. Sheridan Lake Dam Reservoir Operation Study: South Dakota School of Mines & Technology, unpublished master of science research project, 2002, 29p.

Klassen, J.F., 1997, Climate change impacts on the hydrology of Spring Creek Basin in the Black Hills of South Dakota using soil and water assessment tool: South Dakota School of Mines and Technology, unpublished master of science thesis, 67p.

Millar, Robert G. & Quick, Michael C. "Stable Width and Depth of Gravel-Bed Rivers with Cohesive Banks." ASCE Journal of Hydraulic Engineering, Vol 124, No 10, 1998.

Minnesota Pollution Control Agency. Stormwater Best Management Practices Manual, St. Paul, MN, 2002.

Mudumala, S.P. South Dakota School of Mines and Technology unpublished data for master of science research project, 1991.

Novotny, Vladimir & Harvey Olem. Water Quality: Prevention, Identification, and Management of Diffuse Pollution. NewYork: Van Nostrand Reinhold, 1994.

Peck, David V., Lazorchak, James M. and Donald J. Klemm eds. Environmental Monitoring and Assessment Program – Surface Waters: Western Pilot Study Filed operations Manual for Wadeable Streams. National Health and Environmental Effects Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, research Triangle park, NC. April 2001

Reckhow, Kenneth H. & Chapra, Steven C. Engineering Approaches For Lake Management, Volume1: Data Analysis and Empirical Modeling. Boston: Butterworth Publishers, 1983.

Ritter, William F. and Abel Shirmohammadi, ed. Agricultural Nonpoint Source Pollution: Watershed Management and Hydrology. CRC Press LLC, 2001.

South Dakota Department of Environment and Natural Resources. South Dakota Total Maximum Daily Load Waterbody List 2002: Pierre, SD 2002.

South Dakota Deptartment of Game, Fish & Parks. Sheridan Lake, Site Map, 1987.

South Dakota Department of Health. Reprt on pollution and water supply problems in the Spring Ceek Draingae-Sheridan Lake to Oreville. The Division of Sanitary Engineering South Dakota Department of Health, Pierre, SD, 1969.

South Dakota Department of Water & Natural Resources. Black Hills Lakes Preliminary Study. Pierre, SD, 1988.

Stewart, K.R. and Thilenius, C.A. Stream and Lake Inventory and Classification in the Black Hills of South Dakota. SD Department of Game, Fish and Parks, Rapid City, SD, 1964

US Department of Agriculture, Soil Survey of Custer and Pennington Counties, Black Hills Parts, South Dakota, Soil Conservation Service, 1990.

U.S. Environmental Protection Agency. Preliminary report on Sheridan Lake Pennington County, South Dakota EPA Region VIII, United States Environmental Protection Agency, Las Vegas, NV, 1976.

Walker, William W. Simplified Procedures for Eutrophication Assessment and Prediction: User Manual. Instruction Report W-96-2 (Updated April 1999), United States Army Engineer Waterways Experiment Station, Vicksburg, MS, 1996.

Wetzel, Robert G. Limnology: Lake and River Ecosystems 3rd Ed. Academic Press, 2001.

Williamson, Joyce. Hydrologist USGS. Personal communication, July 11, 2003.

APPENDIX A

"Quality Assurance / Quality Control"

Field Duplicate Samples

StationID	VisitCmts	StartDate	Ammonia	Nitrate	TKN	Total_P	Ortho_P	TOC
SL-2	Lower Sample	6/7/02	0.24	0.025	0.6	0.051	0.038	4.1
SL-2	Lower, Duplicate	6/7/02	0.24	0.025	0.6	0.049	0.039	4.1
			0%	0%	0%	-4%	3%	0%
SL-1	Upper Sample	8/14/02	0.025	0.025	0.6	0.01	0.0083	4.2
SL-1	Surface, Duplicate	8/14/02	0.025	0.025	0.6	0.022	0.0041	4.3
			0%	0%	0%	120%	-51%	2%
SL-1	Upper Sample	10/21/02	0.025	0.025	0.9	0.034	0.0159	4.7
SL-1	Surface, Duplicate	10/21/02	0.025	0.025	0.6	0.035	0.0166	4.2
			0%	0%	-33%	3%	4%	-11%
SL-1	Surface Sample	4/15/03	0.025	0.025	0.25	0.01	0.0035	3.9
SL-1	Surface, Duplicate	4/15/03	0.025	0.025	0.52	0.035	0.032	4.2
			0%	0%	***	250%	814%	8%
SL-1	Surface Sample	6/4/03	0.025	0.025	0.56	0.014	0.0035	4.2
SL-1	Surface, Duplicate	6/4/03	0.025	0.025	0.25	0.013	0.0035	4.3
			0%	0%	***	-7%	0%	2%
SL-1	Surface Sample	1/21/03	0.025	0.025	0.25	0.059	0.0168	5
SL-1	Surface, Duplicate	1/21/03	0.025	0.025	0.76	0.057	0.0188	4.7
			0%	0%	***	-3%	12%	-6%
	Mean	Original	0.061	0.025	0.527	0.030	0.014	4.35
		Duplicates	0.061	0.025	0.555	0.035	0.019	4.30
			0%	0%	5%	19%	33%	-1%
	Std Dev	Original	0.088	0.000	0.247	0.022	0.013	0.414
		Duplicates	0.088	0.000	0.169	0.016	0.014	0.210

Field Blank Samples

Date	6/4/2003	4/16/2003	1/23/2003	10/21/2002	8/27/2002	6/7/2002
Lake	Sheridan	Sheridan	Sheridan	Sheridan	Mitchell	Sheridan
Time	12:35	15:45	10:30	12:15	11:00	10:40
E-coli				nd	nd	nd
Fecal				nd	nd	nd
Total Coli						nd
Alkalinity	nd	nd	20	10	nd	6
Total Solids	6	nd	nd	nd	nd	nd
TSS	nd	nd	nd	nd	nd	nd
VSS	nd	nd	nd	nd	nd	<5
DOC	nd	nd	nd	nd	nd	
TOC	0.3	0.3	0.4	0.2	nd	
Ammonia	nd	nd	nd	nd	nd	nd
TKN	nd	nd	nd	nd	nd	nd
NO23	nd	nd	nd	nd	nd	nd
Ortho P	nd	nd	nd	nd	nd	nd
TP	nd	0.010	0.018	0.015	nd	0.019

APPENDIX B

"FLUX input data"

All Nutrient Concentrations are in mg/L

Nutrient Outflow from Sheridan Lake

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
13-May-02	21.14	0.06	0.025	0.25	0.014	0.012	0.275
23-May-02	18.17	0.025	0.025	0.6	0.023	0.005	0.625
29-May-02	18.17	0.025	0.025	0.25	0.012	0.005	0.275
7-Jun-02	14.55	0.025	0.025	0.25	0.022	0.005	0.275
18-Jun-02	7.15	0.025	0.025	0.25	0.013	0.005	0.275
8-Jul-02	2.53	0.05	0.08	0.25	0.029	0.0183	0.33
10-Jul-02	2.53	0.025	0.025	0.25	0.015	0.002	0.275
12-Aug-02	1.76	0.025	0.025	0.25	0.015	0.0046	0.275
14-Aug-02	1.09	0.025	0.025	0.5	0.01	0.002	0.525
9-Sep-02	3.39	0.025	0.06	0.6	0.02	0.005	0.66
24-Sep-02	3.86	0.025	0.025	0.6	0.018	0.002	0.625
7-Oct-02	3.86	0.025	0.025	0.25	0.02	0.0088	0.275
21-Oct-02	3.39	0.06	0.025	0.7	0.043	0.0234	0.725
4-Nov-02	3.86	0.025	0.025	0.6	0.056	0.0218	0.625
23-Jan-03	1.40	0.025	0.025	0.76	0.043	0.017	0.785
28-Jan-03	1.60	0.06	0.08	0.25	0.036	0.024	0.33
18-Feb-03	2.70	0.07	0.025	1.1	0.036	0.0186	1.125
16-Mar-03	17.39	0.05	0.05	0.25	0.036	0.021	0.3
20-Mar-03	19.38	0.025	0.05	0.25	0.074	0.05	0.3
15-Apr-03	12.86	0.025	0.025	0.57	0.013	0.007	0.595
7-May-03	43.91	0.025	0.025	0.53	0.035	0.022	0.555
20-May-03	29.05	0.025	0.025	0.25	0.025	0.007	0.275
4-Jun-03	20.91	0.025	0.025	0.59	0.012	0.0035	0.615

Nutrient Loading for SCT1

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
14-Apr-91	8.26	0.021	0.004	1.9	0.027	0.011	1.927
18-Apr-91	8.70	0.026	0.01	0.3	0.056	0.016	0.356
25-Apr-91	14.60	0.017	0.005	0.3	0.024	0.029	0.324
12-May-91	130.00	0.043	0.014	1.1	0.159	0.176	1.259
19-May-91	136.00	0.04	0.007	0.7	0.107	0.065	0.807
20-Jun-91	68.60	0.025	0.003	0.5	0.087	0.082	0.587
26-Jun-91	49.00	0.014	0.003	0.5	0.06	0.061	0.560
16-Jul-91	33.40	0.018	0.006	0.5	0.119	0.084	0.619
16-Aug-91	14.70	0.002	0.003	0.4	0.065	0.03	0.465
03-Sep-91	8.80	0.02	0.01	0.5	0.05	0.06	0.550
10-Sep-91	7.23	0.002	0.001	0.3	0.037	0.028	0.337
23-Nov-91	7.30	0.013	0.008	0.2	0.141	0.012	0.341
13-Jan-92	2.50	0.041	0.007	0.2	0.277	0.018	0.477
07-May-02	15.00	0.05		0.25	0.025	0.0105	0.275
29-May-02	16.00	0.025		0.25	0.025	0.023	0.275
13-Jun-02	9.70	0.025		0.25	0.025	0.032	0.275
08-Jul-02	4.30	0.025		0.25	0.025	0.045	0.275
12-Aug-02	2.40	0.025		0.25	0.025	0.023	0.275
09-Sep-02	26.00	0.025		1.8	0.22	0.35	2.020
07-Oct-02	4.30	0.025		0.6	0.025	0.018	0.625
04-Nov-02	3.90	0.025		0.25	0.12	0.018	0.370
16-Jan-03	2.00	0.21		0.25	0.68	0.015	0.930
16-Mar-03	17.00	0.14		1.5	0.2	0.24	1.700
19-Mar-03	22.00					0.3	1.900
20-Mar-03	12.00	0.19		1.2	0.32	0.16	1.520
20-May-03	30.00	0.025		0.56	0.025	0.019	0.585

Nutrient Loading for HCT1

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
07-May-02	1.06	0.05	0.16	0.25	0.014	0.0103	0.41
29-May-02	1.13	0.025	0.025	0.25	0.012	0.005	0.275
13-Jun-02	0.69	0.12	0.025	0.25	0.027	0.0201	0.275
08-Jul-02	0.47	0.025	0.025	0.25	0.017	0.005	0.275
12-Aug-02	0.63	0.025	0.025	0.25	0.0111	0.019	0.275
05-Aug-02	1.5	0.05	0.1	0.25	0.056	0.0265	0.35
09-Sep-02	1.04	0.025	0.025	0.25	0.02	0.0127	0.275
07-Oct-02	0.91	0.025	0.025	0.9	0.056	0.131	0.925
04-Nov-02	0.9	0.025	0.08	0.6	0.015	0.002	0.68
28-Jan-03	0.5	0.025	0.29	0.25	0.038	0.0308	0.54
16-Mar-03	0.5	0.025	0.15	0.25	0.036	0.023	0.4
20-Mar-03	0.5	0.025	0.24	0.25	0.035	0.02	0.49
20-May-03	1.3	0.025	0.07	0.25	0.015	0.007	0.32

Nutrient Loading For UKT1

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
07-May-02	0.14	0.1	0.1	0.25	0.022	0.0212	0.35
29-May-02	0.10	0.07	0.025	0.25	0.023	0.014	0.275
13-Jun-02	0.07	0.28	0.025	0.5	0.12	0.089	0.525
08-Jul-02	0.03	0.46	0.09	0.25	0.023	0.0204	0.34
12-Aug-02	0.04	0.42	0.05	0.25	0.038	0.0262	0.3
09-Sep-02	0.06	0.014	0.06	0.25	0.036	0.0193	0.31
07-Oct-02	0.05	0.25	0.05	0.25	0.017	0.0173	0.3
04-Nov-02	0.07	0.37	0.025	0.25	0.016	0.0153	0.275
16-Jan-03	0.10	0.6	0.05	0.25	0.016	0.0137	0.3
16-Mar-03	0.17	0.09	0.025	0.25	0.035	0.014	0.275
20-Mar-03	0.15	0.09	0.13	0.82	0.14	0.086	0.95
20-May-03	0.30	0.025	0.025	0.25	0.008	0.007	0.275

Nutrient Loading For PCT1

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
07-May-02	0.53	0.05	0.025	0.25	0.06	0.0576	0.275
30-May-02	0.42	0.025	0.025	0.5	0.12	0.106	0.525
13-Jun-02	0.35	0.2	0.07	1.8	0.21	0.177	1.87
08-Jul-02	0.11	0.11	0.06	0.6	0.14	0.133	0.66
05-Aug-02	0.24	0.3	0.4	2.1	1.5	0.992	2.5
12-Aug-02	0.07	0.16	0.08	1.8	0.14	0.0126	1.88
09-Sep-02	1.06	0.37	2.8	9.7	2.8	2.04	12.5
07-Oct-02	0.15	0.025	0.025	0.25	0.053	0.0428	0.275
04-Nov-02	0.12	0.025	0.05	0.25	0.039	0.0331	0.3
16-Jan-03	0.03	0.19	0.17	0.25	0.051	0.0497	0.42
16-Mar-03	0.85	0.025	0.17	1.3	0.37	0.29	1.47
20-Mar-03	2.31	0.23	0.26	1.7	0.31	0.24	1.96
20-May-03	1.53	0.025	0.07	0.52	0.097	0.078	0.59
13-Jun-03	1.36	0.14	0.35	3.3	0.7	0.44	3.65

Nutrient Loading For SCT2

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
07-May-02	13.26	0.05	0.025	0.6	0.03	0.0145	0.625
28-May-02	16.02	0.025	0.025	0.25	0.022	0.015	0.275
13-Jun-02	9.71	0.025	0.025	0.25	0.024	0.015	0.275
08-Jul-02	4.08	0.09	0.025	0.6	0.051	0.0253	0.625
12-Aug-02	1.29	0.05	0.025	0.8	0.038	0.0172	0.825
09-Sep-02	10.72	0.025	0.025	1.1	0.076	0.0154	1.125
07-Oct-02	4.31	0.025	0.06	0.25	0.022	0.0097	0.31
04-Nov-02	5.29	0.04	0.16	0.25	0.017	0.0087	0.41
16-Jan-03	0.82	0.36	0.66	0.75	0.029	0.0226	1.41
16-Mar-03	10.24	0.17	0.18	1.3	0.18	0.091	1.48
20-Mar-03	16.76	0.16	0.3	0.86	0.085	0.043	1.16
20-May-03	22.79	0.025	0.025	0.25	0.027	0.013	0.275

Nutrient Loading For SCT3

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
07-May-02	17.17	0.05	0.05	0.6	0.016	0.0119	0.65
28-May-02	17.17	0.025	0.025	0.25	0.032	0.019	0.275
13-Jun-02	11.13	0.025	0.025	0.25	0.022	0.015	0.275
08-Jul-02	3.50	0.08	0.1	0.25	0.046	0.0365	0.35
12-Aug-02	3.27	0.025	0.024	0.25	0.015	0.0134	0.274
09-Sep-02	11.38	0.025	0.34	1.2	0.24	0.112	1.54
07-Oct-02	6.37	0.025	0.12	0.25	0.02	0.0106	0.37
04-Nov-02	9.75	0.18	0.26	0.5	0.018	0.0113	0.76
16-Jan-03	0.79	0.34	0.7	0.58	0.029	0.0169	1.28
16-Mar-03	15.00	0.12	0.22	1	0.14	0.069	1.22
20-Mar-03	16.20	0.11	0.29	0.64	0.065	0.038	0.93
20-May-03	26.86	0.025	0.025	0.25	0.026	0.012	0.275

Nutrient Loading For SCT4

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
13-May-02	15.99	0.025	0.07	0.25	0.034	0.029	0.32
28-May-02	14.50	0.025	0.025	0.25	0.031	0.023	0.275
13-Jun-02	9.96	0.07	0.025	0.25	0.025	0.016	0.275
08-Jul-02	3.23	0.11	0.08	0.25	0.043	0.0333	0.33
12-Aug-02	3.27	0.2	0.23	0.7	0.02	0.018	0.93
05-Aug-02	13.00	0.13	0.32	1.6	1.8	1.42	1.92
09-Sep-02	10.77	0.06	0.21	0.6	0.11	0.0582	0.81
21-Aug-02	5.00	0.15	0.57	2.7	0.54	0.331	3.27
07-Oct-02	6.37	0.12	0.1	0.25	0.046	0.0286	0.35
04-Nov-02	9.75	0.22	0.15	0.5	0.02	0.0142	0.65
16-Jan-03	0.79	0.51	0.53	0.81	0.03	0.026	1.34
16-Mar-03	15.00	0.12	0.23	1	0.16	0.076	1.23
20-Mar-03	11.70	0.1	0.28	0.65	0.82	0.43	0.93
20-May-03	22.50	0.025	0.025	0.25	0.026	0.013	0.275
13-Jun-03	15.54	0.08	0.09	0.87	0.1	0.05	0.96

Nutrient Loading For SCT5

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
13-May-02	21.95	0.025	0.07	0.25	0.02	0.022	0.32
28-May-02	16.34	0.025	0.025	0.25	0.05	0.034	0.275
13-Jun-02	7.72	0.025	0.025	0.25	0.023	0.018	0.275
08-Jul-02	3.80	0.08	0.025	0.25	0.056	0.039	0.275
12-Aug-02	2.32	0.025	0.025	0.5	0.029	0.0119	0.525
09-Sep-02	13.64	0.025	0.19	0.6	0.092	0.0541	0.79
07-Oct-02	4.15	0.025	0.025	0.25	0.016	0.0075	0.275
04-Nov-02	4.84	0.025	0.11	0.25	0.016	0.0064	0.36
16-Jan-03	0.68	0.025	0.39	0.25	0.011	0.0096	0.64
16-Mar-03	15.50	0.06	0.19	0.98	0.17	0.072	1.17
20-Mar-03	11.00	0.09	0.27	0.8	0.15	0.095	1.07
20-May-03	24.50	0.025	0.025	0.25	0.026	0.012	0.275

Nutrient Loading For NCT1

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
13-May-02	2.26	0.025	0.025	0.25	0.015	0.011	0.275
28-May-02	2.76	0.025	0.025	0.25	0.018	0.012	0.275
13-Jun-02	3.33	0.025	0.025	0.25	0.021	0.013	0.275
08-Jul-02	1.29	0.025	0.025	0.25	0.023	0.0138	0.275
12-Aug-02	0.74	0.05	0.025	0.6	0.054	0.0263	0.625
09-Sep-02	0.74	0.025	0.025	0.8	0.049	0.0168	0.825
07-Oct-02	0.58	0.025	0.025	0.6	0.037	0.0136	0.625
04-Nov-02	0.58	0.025	0.025	0.25	0.023	0.0132	0.275
16-Jan-03	0.12	0.025	0.025	0.68	0.04	0.0131	0.705
16-Mar-03	1.50	0.025	0.58	0.025	0.18	0.05	0.605
20-Mar-03	2.00	0.025	0.1	0.51	0.045	0.021	0.61
20-May-03	8.75	0.025	0.06	0.25	0.024	0.012	0.31

Nutrient Loading For SCT6

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
13-May-02	9.22	0.025	0.06	0.25	0.02	0.018	0.31
29-May-02	9.49	0.025	0.025	0.25	0.028	0.019	0.275
13-Jun-02	6.27	0.025	0.025	0.25	0.024	0.018	0.275
08-Jul-02	2.93	0.05	0.025	0.25	0.046	0.0361	0.275
05-Aug-02	8.96	0.08	0.1	1.1	0.92	0.67	1.2
12-Aug-02	2.31	0.025	0.025	0.25	0.016	0.0157	0.275
22-Aug-02	2.40	0.025	0.08	0.6	0.072	0.0356	0.68
09-Sep-02	8.00	0.025	0.08	0.25	0.065	0.0332	0.33
07-Oct-02	4.75	0.025	0.025	0.25	0.016	0.0076	0.275
04-Nov-02	5.60	0.025	0.025	0.25	0.017	0.0082	0.275
16-Jan-03	0.77	0.07	0.32	0.25	0.014	0.0137	0.57
16-Mar-03	15.20	0.07	0.17	1.1	0.16	0.089	1.27
20-Mar-03	15.40	0.06	0.23	0.85	0.14	0.08	1.08
20-May-03	14.92	0.025	0.025	0.25	0.028	0.016	0.275
12-Jun-03	13.00	0.025	0.025	0.51	0.04	0.02	0.535

Nutrient Loading For SCT7

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
13-May-02	15.57	0.025	0.05	0.25	0.022	0.017	0.3
29-May-02	9.90	0.025	0.025	0.25	0.048	0.033	0.275
13-Jun-02	5.86	0.025	0.025	0.25	0.035	0.026	0.275
08-Jul-02	1.80	0.025	0.025	0.25	0.04	0.0313	0.275
05-Aug-02	3.00	0.025	0.025	0.25	0.079	0.057	0.275
12-Aug-02	1.29	0.025	0.025	0.25	0.045	0.0355	0.275
09-Sep-02	8.54	0.025	0.025	0.8	0.17	0.0943	0.825
07-Oct-02	2.49	0.025	0.025	0.25	0.019	0.0157	0.275
04-Nov-02	2.65	0.025	0.025	0.25	0.017	0.0136	0.275
16-Jan-03	0.63	0.025	0.13	0.25	0.012	0.0104	0.38
16-Mar-03	12.50	0.06	0.16	1.1	0.17	0.079	1.26
20-Mar-03	4.00	0.025	0.2	0.67	0.096	0.053	0.87
20-May-03	11.79	0.025	0.025	0.57	0.025	0.016	0.595

Nutrient Loading For SGT1

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
13-May-02	3.35	0.025	0.05	0.025	0.17	0.172	0.075
29-May-02	1.66	0.025	0.025	0.25	0.056	0.047	0.275
13-Jun-02	0.70	0.025	0.025	0.25	0.064	0.054	0.275
08-Jul-02	0.20	0.06	0.025	0.25	0.094	0.0898	0.275
05-Aug-02	1.55	0.025	0.05	0.5	0.21	0.14	0.55
12-Aug-02	0.24	0.025	0.025	0.25	0.088	0.0832	0.275
09-Sep-02	2.16	0.025	0.07	1.2	0.35	0.257	1.27
07-Oct-02	0.46	0.025	0.025	0.25	0.076	0.0655	0.275
04-Nov-02	0.68	0.025	0.025	0.25	0.056	0.0479	0.275
16-Jan-03	0.10	0.025	0.13	0.25	0.031	0.0195	0.38
16-Mar-03	1.21	0.025	0.13	0.25	0.12	0.099	0.38
20-Mar-03	1.98	0.025	0.16	0.25	0.09	0.082	0.41
20-May-03	2.57	0.025	0.025	0.25	0.047	0.039	0.275

Nutrient Loading For SCT8

date	flow, cfs	NH4	NO23	TKN	TP	OP	TN
13-May-02	7.33	0.025	0.05	0.25	0.014	0.013	0.3
29-May-02	5.58	0.025	0.025	0.25	0.014	0.005	0.275
13-Jun-02	2.87	0.025	0.025	0.25	0.011	0.01	0.275
08-Jul-02	1.70	0.025	0.025	0.25	0.02	0.0134	0.275
12-Aug-02	0.69	0.025	0.025	0.7	0.0705	0.0409	0.725
09-Sep-02	7.65	0.025	0.05	0.6	0.12	0.0431	0.65
07-Oct-02	1.32	0.025	0.025	0.25	0.016	0.0104	0.275
04-Nov-02	1.02	0.025	0.025	0.25	0.016	0.0095	0.275
16-Jan-03	0.27	0.025	0.18	0.25	0.053	0.0525	0.43
16-Mar-03	4.00	0.08	0.16	1.2	0.15	0.063	1.36
20-Mar-03	2.40	0.025	0.21	0.56	0.059	0.026	0.77
20-May-03	6.40	0.025	0.025	0.25	0.017	0.008	0.275

APPENDIX C

"Input Code for Sheridan Lake Model"

```
Dim nloads As Integer
Dim t(200), Q(200), pin(200) As Single
Dim m(12), d(12) As Variant
Dim Thw, Ths, strat, tyr, tspr, taut, tsum, twin As Single
Dim DOiw, DOis, Hh, vro, vrwa, vrsa, vs, vr, vb, A2, Vol1, Vol2 As Single
Dim Vol3, Vol4, Day, mo, percent, num As Single

Sub Calculator()
Dim tout(200), pout1(200), pout2(200), pout3(200), pout4(200), checkm(365) As Single
Dim avgp1(365), avgp2(365), avgp3(365), avgp4(365), phosin(365), phosout(365) As
Single
Dim mpin(200), mpout(200) As Single

'input parameters
Sheets("calc").Select
Range("b6").Select
Vol1 = ActiveCell.Value
Range("b7").Select
Vol2 = ActiveCell.Value
Range("b8").Select
A3 = ActiveCell.Value
Range("b9").Select
A4 = ActiveCell.Value
Range("b10").Select
Hh = ActiveCell.Value

Range("b12").Select
p1 = ActiveCell.Value
Range("b13").Select
p3 = ActiveCell.Value
Range("b14").Select
p4 = ActiveCell.Value
Range("b15").Select
DOis = ActiveCell.Value
Range("b16").Select
DOiw = ActiveCell.Value

Range("b18").Select
H3 = ActiveCell.Value
Range("b19").Select
por3 = ActiveCell.Value
Range("b20").Select
rho3 = ActiveCell.Value
Range("b21").Select
vr3 = ActiveCell.Value
Range("b22").Select
coef3w = ActiveCell.Value
Range("b23").Select
```

```
coef3s = ActiveCell.Value
Range("b24").Select
vb3 = ActiveCell.Value

Range("b26").Select
H4 = ActiveCell.Value
Range("b27").Select
por4 = ActiveCell.Value
Range("b28").Select
rho4 = ActiveCell.Value
Range("b29").Select
vr4 = ActiveCell.Value

Range("b32").Select
vb4 = ActiveCell.Value

Range("b34").Select
vs1 = ActiveCell.Value
Range("b35").Select
vs2 = ActiveCell.Value
Range("b36").Select
ensrps = ActiveCell.Value
Range("b37").Select
ensrpw = ActiveCell.Value
Range("b38").Select
hnsrps = ActiveCell.Value
Range("b39").Select
hnsrpw = ActiveCell.Value
Range("b40").Select
vr2s = ActiveCell.Value
Range("b41").Select
vr2m = ActiveCell.Value

Range("b43").Select
Ths = ActiveCell.Value
Range("b44").Select
Thw = ActiveCell.Value
Range("b45").Select
tspr = ActiveCell.Value
Range("b46").Select
tsum = ActiveCell.Value
Range("b47").Select
taut = ActiveCell.Value
Range("b48").Select
twin = ActiveCell.Value

'input division of flow
Range("k5").Select
```

```
 For i = 1 To 12
  m(i) = ActiveCell.Value
  ActiveCell.Offset(0, 1).Select
  d(i) = ActiveCell.Value
  ActiveCell.Offset(1, -1).Select
 Next i

'calculate parameters
H3 = H3 / 100
H4 = H4 / 100
Vol3 = A3 * H3
Vol4 = A4 * H4
p2 = p1
p3 = p3 * rho3 * (1000) * (1 - por3)
p4 = p4 * rho4 * (1000) * (1 - por4)
vb3 = vb3 / 1000
vb4 = vb4 / 1000
vr3s = vr3 * coef3s
vr3w = vr3 * coef3w
vr4s = vr4
vr4w = vr4 * 1.08 ^ (Thw - Ths)
vro = 0

'check length of forcing function
Range("e4").Select
Selection.End(xlDown).Select
bottom = ActiveCell.Row
nloads = bottom - 5
If nloads > 1000 Then nloads = 0

'input forcing functions
Range("e5").Select
For i = 0 To nloads
  t(i) = ActiveCell.Value
  ActiveCell.Offset(0, 1).Select
  Q(i) = ActiveCell.Value
  ActiveCell.Offset(0, 1).Select
  pin(i) = ActiveCell.Value
  ActiveCell.Offset(1, -2).Select
Next i

pave = p1
tout(0) = t(0)
pout1(0) = pave
pout2(0) = pave
pout3(0) = p3
pout4(0) = p4
tint = tt + t(0)
```

```
‘Clear output worksheet from previous run
   Sheets("output").Select
    Sheets("output").Range("j3:m367").Formula = ""
    Range("j3").Select

For i = 0 To nloads

  AHOD = 0.086 * pave ^ 0.478
  AHODs = AHOD
  AHODw = AHOD * 1.08 ^ (Thw - Ths)


 For j = 1 To 365
  Day = 0 + j
  Call Month(Day, mo)
  Qinput = Q(i) * m(mo) / d(mo)

  'epilimnion settling
  If mo > 4 And mo < 11 Then
   vse = vs1 * ensrps
   Else: vse = vs1 * ensrpw
  End If
  If Day < tspr Then
   vse2 = vse
   ElseIf Day >= tspr And Day < tsum Then
   vse2 = vr2m
   ElseIf Day >= tsum And Day < taut Then
   vse2 = vse
   ElseIf Day >= taut And Day < twin Then
   vse2 = vr2m
   ElseIf Day >= twin Then
   vse2 = vse
  End If

  'hypolimnion settling
 'If mo > 4 And mo < 10 Then
   'vsh = vs2 * hnsrps
   'Else: vsh = vs2 * hnsrpw
 'End If

  If Day < tspr Then
   vsh = vs2 * hnsrpw
   ElseIf Day >= tspr And Day < tsum Then
   vsh = vs2 * hnsrpw
   ElseIf Day >= tsum And Day < taut Then
   vsh = vs2 * hnsrps
   ElseIf Day >= taut And Day < taut + 10 Then
```

```
 vsh = vs2 * hnsrps * 8
 ElseIf Day >= taut + 10 And Day < twin Then
 vsh = vs2 * hnsrpw
 ElseIf Day >= twin Then
 vsh = vs2 * hnsrpw
End If

'shallow sed recycle
If mo < 5 Then vrss = vr3 * coef3w
If mo > 4 And mo < 11 Then vrss = vr3 * coef3s
If mo > 10 Then vrss = vr3 * coef3w


'deep sed recycle
      If Day < tspr Then
      ox = DOiw - AHODw / Hh * (Day - twin + 365)
      If ox < 1.5 Then
        ox = 1.5
        vrds = vr4w
      Else
        vrds = vro
      End If
    ElseIf Day >= tspr And Day < tsum Then
      vrds = vro
      ox = DOis
    ElseIf Day >= tsum And Day < taut Then
      ox = DOis - AHODs / Hh * (Day - tsum)
      If ox < 1.5 Then
        ox = 1.5
        vrds = vr4s
      Else
        vrds = vro
      End If
    ElseIf Day >= taut And Day < twin Then
      vrds = vro
      ox = DOiw
    ElseIf Day >= twin Then
      ox = DOiw - AHODw / Hh * (Day - twin)
      If ox < 1.5 Then
        ox = 1.5
        vrds = vr4w
      Else
        vrds = vro
      End If
    End If

'hypolimnion transfer
  If Day < tspr Then
```

```
  vrh = vr2s
  ElseIf Day >= tspr And Day < tsum Then
  vrh = vr2m
  ElseIf Day >= tsum And Day < taut Then
  vrh = vr2s
  ElseIf Day >= taut And Day < twin Then
  vrh = vr2m
  ElseIf Day >= twin Then
  vrh = vr2s
 End If

 dp1dt = Qinput * 365 * pin(i) - Qinput * 365 * p1 - vse * (A3) * p1 + vrss * A3 * p3 +
vrh * A4 * p2 - vse2 * A4 * p1
 dp2dt = vse2 * A4 * p1 - vrh * A4 * p2 - vsh * A4 * p2 + vrds * A4 * p4
 dp3dt = vse * A3 * p1 - vrss * A3 * p3 - vb3 * A3 * p3
 dp4dt = vsh * A4 * p2 - vrds * A4 * p4 - vb4 * A4 * p4
 p1 = p1 + dp1dt * (1 / 365) / Vol1
 p2 = p2 + dp2dt * (1 / 365) / Vol2
 p3 = p3 + dp3dt * (1 / 365) / Vol3
 p4 = p4 + dp4dt * (1 / 365) / Vol4
 pave = p1

 checkm(j) = p4 / (rho4 * (1000) * (1 – por4))
 ‘individual day check of sediment phosphorus levels

 avgp1(j) = p1
 avgp2(j) = p2
 avgp3(j) = p3
 avgp4(j) = p4
 'Mass balance check
 phosin(j) = Qinput * pin(i)
 phosout(j) = Qinput * p1 + (vb3 * A3 * p3 + vb4 * A4 * p4) / 365

Next j


'averaging the values instead of year end
sump1 = 0
sump2 = 0
sump3 = 0
sump4 = 0
avp1 = 0
avp2 = 0
avp3 = 0
avp4 = 0
phosinn = 0
phosoutt = 0
```

```
 'mass balance for year
 For j = 1 To 365
    phosinn = phosinn + phosin(j)
    phosoutt = phosoutt + phosout(j)
 Next j

 For j = 1 To 365
  sump1 = sump1 + avgp1(j)
  sump2 = sump2 + avgp2(j)
  sump3 = sump3 + avgp3(j)
  sump4 = sump4 + avgp4(j)
 Next j

 avp1 = sump1 / 365
 avp2 = sump2 / 365
 avp3 = sump3 / (365 * rho3 * (1000) * (1 - por3))
 avp4 = sump4 / (365 * rho4 * (1000) * (1 - por4))
 pave = ((avp1 * Vol1 + avp2 * Vol2) / (Vol1 + Vol2))

 If i > 48 And i < 65 Then
    For k = 1 To 365
     ActiveCell.Formula = checkm(k)
     ActiveCell.Offset(1, 0).Select
    Next k
     ActiveCell.Offset(-365, 1).Select
 End If

 tout(i) = t(i)
 pout1(i) = avp1
 pout2(i) = avp2
 pout3(i) = avp3
 pout4(i) = avp4
 mpin(i) = phosinn / 1000000
 mpout(i) = phosoutt / 1000000

Next i

Sheets("output").Select
Sheets("output").Range("a3:f202").Formula = ""
Range("a3").Select
For i = 0 To nloads
  ActiveCell.Formula = tout(i)
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Formula = pin(i)
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Formula = pout1(i)
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Formula = pout2(i)
```

```
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Formula = pout3(i)
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Formula = pout4(i)
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Formula = mpin(i)
  ActiveCell.Offset(0, 1).Select
  ActiveCell.Formula = mpout(i)
  ActiveCell.Offset(1, -7).Select
Next i

Sheets("calc").Select
Range("h1").Select
Sheets("output").Select
Range("g18").Select
End Sub

Sub Month(Day, mo)
 'this sub assigns a month based on a day
 If Day < 32 Then mo = 1
 If Day < 60 And Day > 31 Then mo = 2
 If Day < 91 And Day > 59 Then mo = 3
 If Day < 121 And Day > 90 Then mo = 4
 If Day < 152 And Day > 120 Then mo = 5
 If Day < 182 And Day > 151 Then mo = 6
 If Day < 213 And Day > 181 Then mo = 7
 If Day < 244 And Day > 212 Then mo = 8
 If Day < 274 And Day > 243 Then mo = 9
 If Day < 305 And Day > 273 Then mo = 10
 If Day < 335 And Day > 304 Then mo = 11
 If Day < 366 And Day > 334 Then mo = 12
End Sub
```